University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Offshore Technology Marine and Subsea Technology	Spring semester, 2012 Open
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Titel of thesis: Subsea in the Kara Sea	
Credits (ECTS): 30	
Key words: Offshore, Arctic, Kara Sea, Subsea installation, Tunnel concept.	Pages: 64 Stavanger, 27.06.2012 Date/year

Abstract.

In this master's thesis the application of subsea technology in the Kara Sea were described. Using date for one perspective structure, several scenarios of field's development were observed; the most important recovery parameters have been evaluated. The analysis of transportation challenges was performed; also the probability estimation for the subsea installation in the Kara Sea was conducted.

Acknowledgements

Special thanks go out to Prof. Ove Tobias Gudmestad and Prof. Anatoly Zolotukhin without whose motivation and encouragement I would not have considered this work. I appreciate their knowledge and skills in many in many areas, and their assistance in writing reports.

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Introduction

To identify a development variant for an oil field in the initial stage, prior to exploration drilling, it is first necessary to compare possible preliminary development concepts. Using a simplified engineering approach to modeling the development, such as assuming a black oil reservoir model, flooding piston displacement and using the equation of material balance yields the initial evaluation of such important parameters of development as: the oil recovery ratio (ORR), the maximum production rate at the "plateau", the optimal number of wells in each of the schemes of development and the time of exploitation.

This work describes the potential development of the Vikulovskay structure, which is located in the license area of the East-Prinovozemelsky-1 at a depth of 300-320 meters and 50 km from the coast of Novaya Zemlya. Due to heavy ice conditions in the Kara Sea and the great depth of water, there are only two concepts of development of this structure:

- to use of subsea production systems

- to use extra-long wells [13]. This is a matter for the future

In this work the physical environmental conditions (bathymetry, ice and soil conditions) have been analyzed to determine the success of subsea solutions in the development of hydrocarbons in the Kara Sea. Detailed maps of the soil environment, prepared by the author in processing data from expeditions conducted between 1960 and 2000's, have been shown. The preliminary evaluation of the parameters of the development in the primary regime (depletion) and two modes to maintain reservoir pressure (water injection and gas injection) have been done.

The application of tunneling concepts for offshore oil and gas fields proposed by a group of specialists from the University of Stavanger and the Gubkin Russian State University of Oil and Gas [4] is also discussed. Furthermore, it is envisaged that a subsea development with subsea drilling rig and subsea processing and compression equipment might be viable in the future.

Components of subsea production systems, which can be used in the exploitation for Vikulovskay, were described; their main tasks have been named within this work. Using data from the Russian Maritime Register relative to wave statistics in the Kara Sea, the mean estimated time of installation subsea modules, the probability of its performance for the month and for the season have been calculated; the guidance on the technical tools that can perform this operation on the marine environment of the Kara Sea also were provided.

Chapter 1. Environmental conditions in the Kara Sea

1.1. Geographical position [11]

The Kara Sea is a marginal sea. The northern boundary is traced from its east to west from Cape Arctic (located on the island of Komsomolets on the Severnaya Zemlya archipelago) to Cape Kolzat (located on the island of Graham Bell of the archipelago of Franz Josef Land). The western boundary runs from the south of this cape to Cape Gelaniay on the Novaya Zemlya, then along the eastern coast of Novaya Zemlya, along the western boundary of the Strait of Kara Gate, along the western shore of the island Vaygach and along the western boundary of the Strait of Ugra Shar to the Mainland. The eastern boundary is along the shores of the sea islands of the archipelago of Severnaya Zemlya and the eastern boundary of the straits of the Red Army, Shokalski and Vilkitski; and the southern boundary - along the continental coast from Cape White Nose to Cape Pronchishchev (Fig. 1).The area of the Kara Sea is 883.000 km^2.

In the Kara Sea there are many islands and the coastline is very tortuous. Baidaratskaya and the Ob Bay stretch out deep in the Sea and large bays (Gyda, Yenisei and Pyasinsky) are located in the eastern part of the Kara Sea.

In the Kara Sea the bottom topography is uneven; the average depth of the sea is 111 m and the maximum depth 600 m. There is the Central Kara Hill to the north of the mainland with coastal shallow water, which separates the trough of St Anne's (here is the deepest seas - 600 m) in the west and Voronin, with depths over 200 m, in the east.

The East-Novazemelckay Trench extends along the coast of the Novaya Zemlya, with maximum water depth of 500 m.

Depending on the characteristics of ice and hydrometeorological regime, the Kara Sea is traditionally divided into two parts - the south-western and the north-east, the boundary between them is on the line from Cape Desire to the island of Dixon. (Fig. 2)

In the Kara Sea there are several nature reserves, the location of which contributes challenges for the economic activities of people. (Fig. 3)

The Kara Sea is almost non-seismic; however, there were four events with source depths of 10 to 25 km and magnitudes up to 5 on the Richter scale, two of which occurred on the island of the October Revolution. [10]

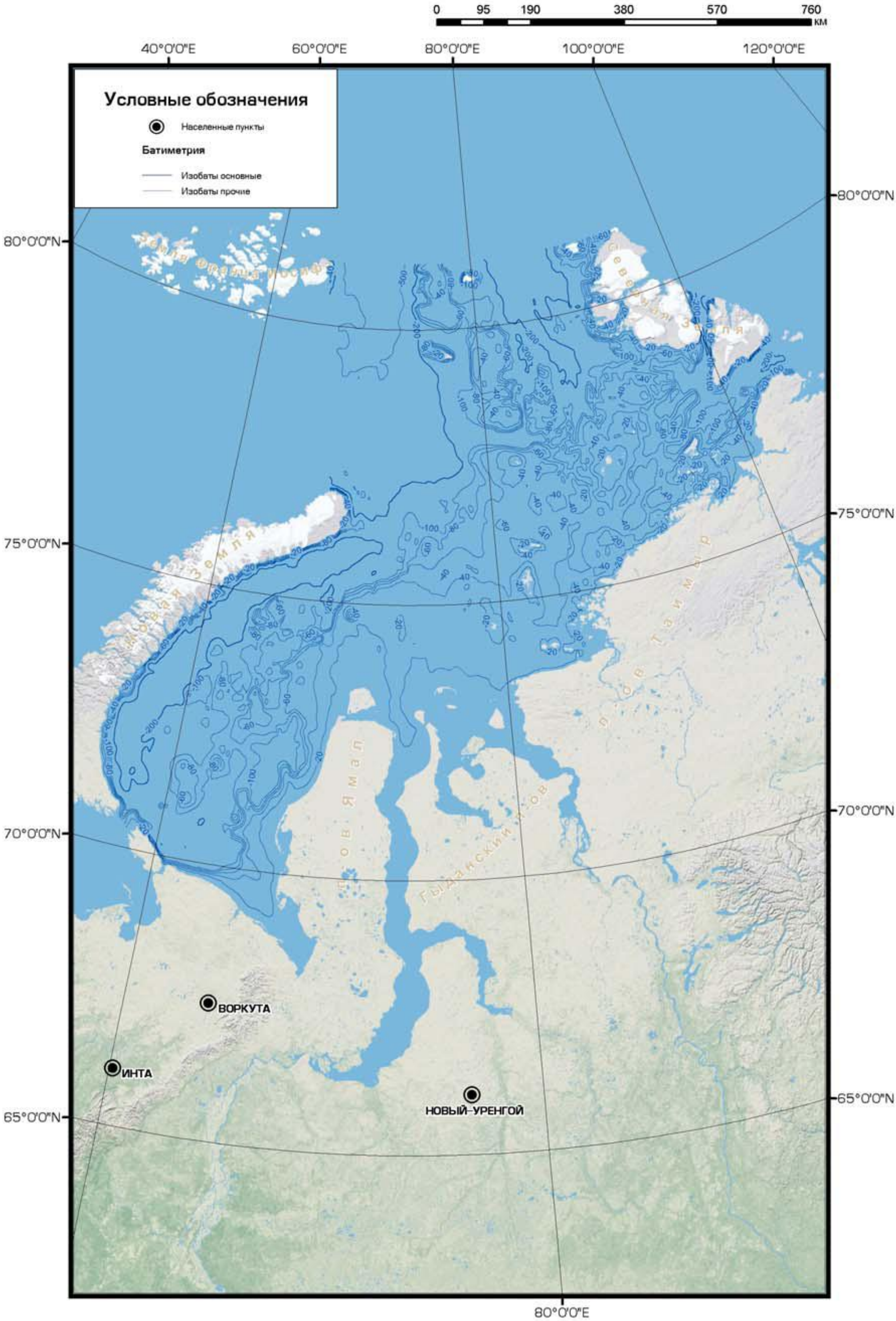

Fig. 1. Kara Sea. Bathymetry map [17]

Fig. 2. Kara Sea. Northern and Southern parts [17]

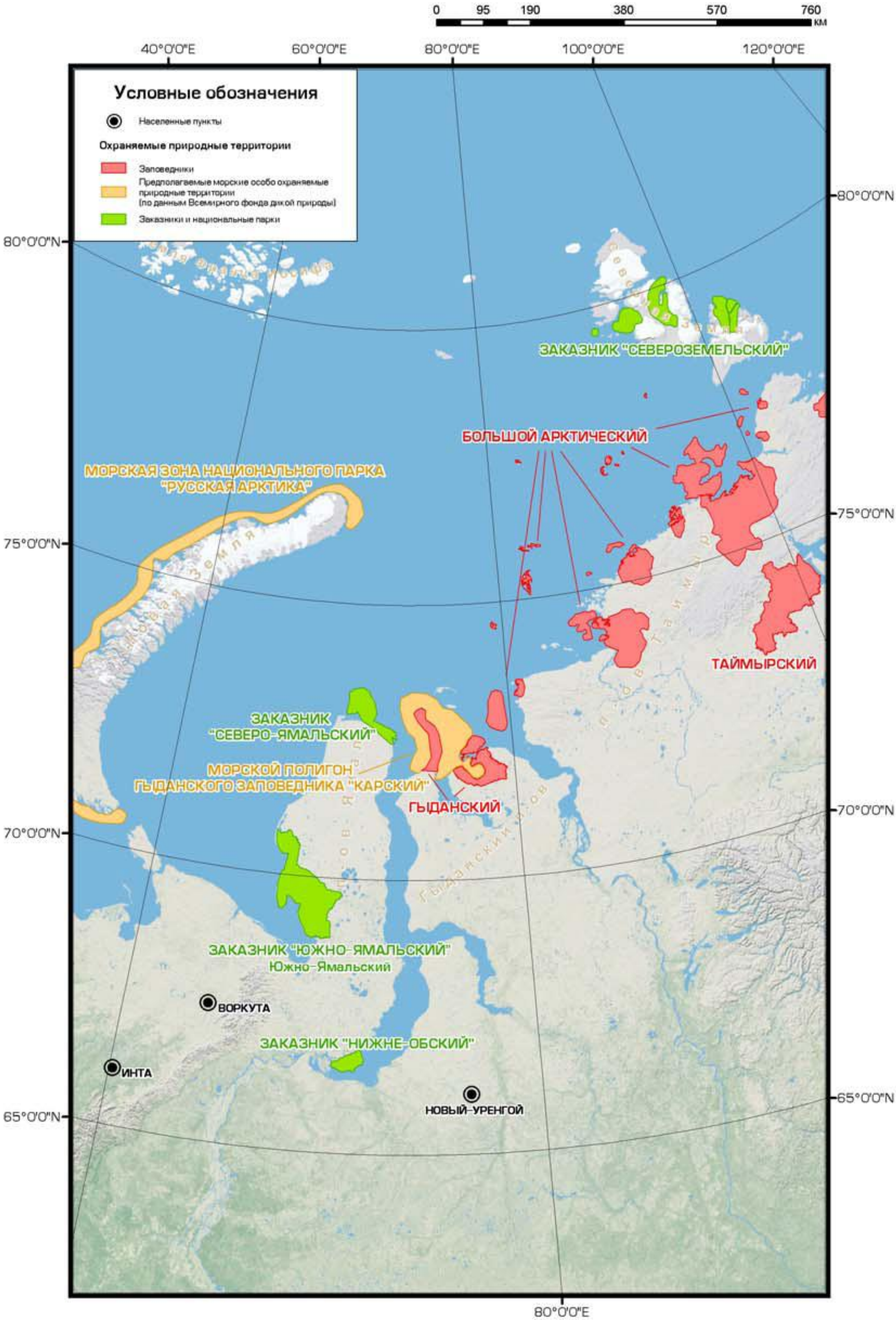

Fig. 3. Reserves adjacent to the area of the Kara Sea [17].

1.2. The climatic conditions [11, 17]

As the Novaya Zemlya is a barrier for warm Atlantic air and water, the polar maritime climate of the Kara Sea is more severe than the climate of the Barents Sea. The air temperature is below 0 ° C retained in the north of the Kara Sea 9-10 months, in the south - 7 - 8 months. The average January temperature is -20 to - 28 ° C (minimum -50 ° C), July -6 to +1 ° C (maximum to +16 ° C). Average wind speed in the summer is 5-6 m/sec, in the winter 7-8 m/sec. The maximum wind speed is 34-40 m/s or more in winter and 24-34 m/s in the summer. The average annual rainfall in the southwestern part of the sea is from 250 to 400 mm; from 200 to 320 mm in the north-east.

The relative humidity is high throughout the year (an average of 80-85% in winter to 90-95% in summer). Fogs at the sea are most frequent in July and August. The number of days with storms – is 1-2 month in the summer months and 6-7 in the winter. The greatest number of storms is observed in the western part of the sea. A local hurricane – the Novaya Zemlya boron is often formed along the coast of Novaya Zemlya. It usually lasts a few hours, but in winter can last 2-3 days.

1.3 The hydrological conditions. [11, 17]

The system of currents in the Kara Sea is provided by circulating water of the Arctic Basin with the adjacent seas. The system of currents is characterized by a cyclonic circulation in the southwestern part and multi-directional flows in the southern, central and northern regions. The flow velocity is usually small. The tides in the Kara Sea are clearly marked, but relatively small (0.5 - 0.8 m), in the Ob Bay - more than 1 m. Speed of tidal currents reaches significant values. The size of waves depends on speed and duration of wind and ice, so the most severe disturbances are in early autumn. Maximum wave height is 8 m

Free flow from the Arctic Basin, a large continental runoff, ice formation and melting determine the magnitude and distribution of salinity. The salinity of the surface waters in the summer varies from 3-5 ° /oo in the mouths of the major rivers and 34 ° /oo in the open sea. The salinity increases from the surface to the bottom. In the winter in the most parts of the sea it is uniformly raised to 30 ° / oo.

1.4. Ice conditions [11]

With respect to the condition of the ice cover, as well as the navigation in ice conditions it may be noted that the Kara Sea consists of two almost independent parts, i.e. in the space between Novaya Zemlya and Severnaya Zemlya is located not one but two Arctic Seas: the south-western area of 335.000 km^2 and the north-eastern area of 495.000 km^2.

Ice formation in the Kara Sea begins in late August - early September in the northeast area, mainly of residual ice, and usually lasts for two and a half months. During the second half of September ice formation extends along the Severnaya Zemlya and the Taimyr Peninsula, and in the Strait of Vilkitski. In early October ice is observed in the entire area of the north-eastern part. (Fig. 4)

From the north-eastern part of the sea freezing is gradually spreading in the south-western part, where it usually starts in the freshened waters of the Ob-Yenisei seaside, as well as along the northern island of Novaya Zemlya. During October and the first half of November a "wave" of ice formation covers a large part of the coastal and open areas of the south-western part of the Sea (Yamal and Novaya Zemlya coast, Baidarata Bay), and in the third week of November the primary forms of ice appear in the Kara Gate Strait.

After freezing in, the sea has a gradually increasing thickness of the ice, which reaches a maximum at the end of the cold period (May).

In the southwestern part of the sea by the end of the period of ice growth, much of the area is occupied by, as a rule, first-year thick ice (over 120 cm thick). In this area in the north their thickness is about 140-160 cm, in the south - about 120-140 cm. and in the polynya the thickness is reduced to less than the 70-120 cm. Before melting in the summer, the young ice (30 cm) occupy about 10 - 15% of the sea, the ice first-year average and thin ice - about 20-25%, while first-year thick - about two-thirds of the area of the sea.

In the northeastern part of the sea, thicker ice is forming. Closer to the Severnaya Zemlya its maximum thickness is about 170-180 cm, and in the rest of the area - about 150-160 cm. Before melting in the summer, the young ice (30 cm) occupy about 5% of the sea, and the average first-year thin ice - about 10% , while first-year fat ice - more than 80%. As a result, 80% thick first-year ice is located in the northeastern part of the sea.

In winter, due to the uneven spatial and temporal drift ice, ice is hummocking, which increases towards to the end of the cold season. In the southwestern part of the sea the hummocking degree is an average of about 2-3 points, and in the north-east - about 3 points (on a 5-point scale). The density of the ice cover is usually 9-10 during the growth of its thickness, and decreases during the loss of the ice cover. Upon reaching young ice thickness of 10-30 cm along the mainland and island coasts a stationary ice - fast ice, seaward boundary is formed of which in the period of greatest development is near the isobaths of 15-20 m. The fast ice formation in the Kara Sea is stretched out in time and takes place over several months. In the northeastern part of the sea ice formation occurs in the middle and second half of October at the Severnaya Zemlya, the western approaches to the Vilkitski strait and along the Taimyr coast. In the southwestern part of the sea ice formation begins in the Ob and Yenisei region (late October - early November), and extends along the Yamal Peninsula (November), and Amderminskogo coast (late November - December).

Polynyas (areas of clear water or young ice thickness up to 30 cm) are formed behind the fast ice during the cold period, the formation of which depends on the direction and stability of the wind. In the southwestern part of the sea is the most stable Ob-Yenisei and Yamal polynya (more repeatable than 80%), while the repeatability of the Amderminskoy polynya is about 70% and the repeatability of the Novaya Zemlya polynyas is 60%.

In the northeastern part of the sea Central Kara and North-western polynyas are the most stable (with a repeatability of 80% and 60% respectively).

Because of the pressure-ice drift in the landfast area and the fast ice to a depth of 20 m, hummocks are formed. Hummocks are common in coastal areas, both among the drifting ice, and in the fast ice. Most often they are observed along the west coast of the Yamal Peninsula, the Ob-Yenisei estuaries close to the beach, and near the Pritaymyrskogo shallow water. The observed maximum values of the geometry of the grounded hummocks are: height of the sails of 10-15 m and 20-25 m depth of the keel

Icebergs are formed from glacier outlets and are observed near the north-east coast of Novaya Zemlya and the west coast of the Severnaya Zemlya archipelago. In the southern coastal regions, icebergs typically do not occur.

In the initial period of melting (June-July) the sea is completely dominated by relatively large amount of ice (7-10 points), but later the area of rare (1-3 points) and sparse amount of ice (4-6 points) increases, so that in the second half of August and in September the amount of ice being 7-10 and 1-6 points are approximately equal.

Breaking of the ice is going on in the initial period of melting of the ice. In the southwestern part of the sea the fast ice is firstly destroyed along the Amderminskogo coast (in June), and then - along the Yamal Peninsula and in the Ob and Yenisei regions (in the first half and to mid-July). In the northeastern part of the sea ice cracking usually begins in early June from the edge of the ice. Most of the fast ice breaks up in July, so that by the end of the month, ice remains only in the narrow coastal area between Minin Skerries and the southern part of the Nordenskiöld Archipelago, as well as in the straits of the Severnaya Zemlya archipelago.

In the southwestern part of the Kara Sea ice melting usually begins in late May or early June. Already in the first half of June, about 10% of area is free of ice by melting of ice in the most delicate area of the polynya. In July, the intensity of thawing increases sharply when there is a break-fast ice and drifting in its transition state, thus by the end of the month about half the area of south-western part of the sea is cleared. Already in the first half of August, the water area is 80-90% completely cleared, and in September the entire southwestern part of the sea is usually free from ice. (Fig. 5)

In the northeastern part of the sea ice melting and cleansing throughout the summer season is slower and the water area is usually full of ice and is not cleared. In June to first half of July, only about 10% of the sea is free ice due to the slow melting of ice in the polynya. In the second half of August, about one third of the sea has cleared, but in September only about half the area of the sea is ice-free. In this case the residual ice is usually located in the north area, as well as along the west coast and the northern shore of the Taimyr Peninsula.

As follows from the peculiarities of the ice regime, the loss of ice in the sea is most intense in July and August. By the end of August, is cleared about 60% of the waters of the Kara Sea; mainly in its south-western part. In September, another 10-15% loss of ice cover occurs in the northern areas of the sea. However, at that time the ice formation begins. In summer, the duration of ice-free period is usually two to four months. At the same time, north of 73^0 N it decreases up to 70-80 days, and to the south – the ice free period is increased to 90-110 days.

In the northeastern part of the sea (due to frequent presence of a residual ice regime) the ice-free periods are more complex. In the north area, along the Novaya Zemlya, as well as in the western approaches to the Strait Vilkitski, the time interval without ice is on average only about 10-20 days (and half the time - in the presence of residual ice – the ice free period is equal to zero). In most of the remaining waters the period without ice area is about 30-40 days, and in the local areas near the border with the south-western part of the sea the ice free period can be increased up to 70-80 days.

For the long-term observation series investigated the frequency of heavy ice conditions in the Kara Sea is about 25%, light - 22% and average - 53%.

Fig. 4. Spread of ice in the autumn in Kara Sea [11,17]

Fig. 5. Spread of ice in the summer in Kara Sea [11,17]

1.5. Soil conditions [12]

Soil conditions in the Kara Sea are of different types, the most common - sand, clay and silt. (Figure 6 and.7) In the distribution of marine Holocene sediments (mQIV), zoning is observed, which is controlled by the present topography of the bottom. In shallow water, especially off the White Islands, Vilkitski and Neupokoeva at depths up to 20m is spread a little layer of fine-grained muddy sands on submarine slopes at the depth interval 20 - 100 m, silt has developed in depressions and in the Ob and Yenisei Bay - clay.

In the shallow southern part of the district, in areas of modern erosion, we find Upper Pleistocene bluish gray clay (lmQIII4) with layers of peat of several tens of centimeters expose. These sediments were deposited in coastal swamps and marshes, and are characterized by an oblique stratification, with the presence of small twigs and leaves of shrub. This, apparently, due to the fact that in the Late Pleistocene time, the shelf was dried under low precipitation. In the cold and dry climatic conditions the ground experienced dehydration, compacted, and as a result acquired a solid consistency.

The deposition of sediments with less dense compacting may indicate a zone of defrosting of permafrost, which occurred during a transgression that followed the fall of sea level. Gas-saturated sediments are recorded on the seismic profiles as "bright spots" or areas of loss of correlation and clarification in the seismic records and have dissected the upper surface, similar to the surfaces of erosion unconformities.

The area of the deep East-Prinovozemelskoy depression is characterized by different bottom conditions compared to the rest of the Kara Sea. Clays make up the bottom, being a small seal under the ice with the complete absence of permafrost. The risk of landslides qualitatively changes the engineering and geological evaluation and the complexity of this area in terms of the use of subsea production systems.

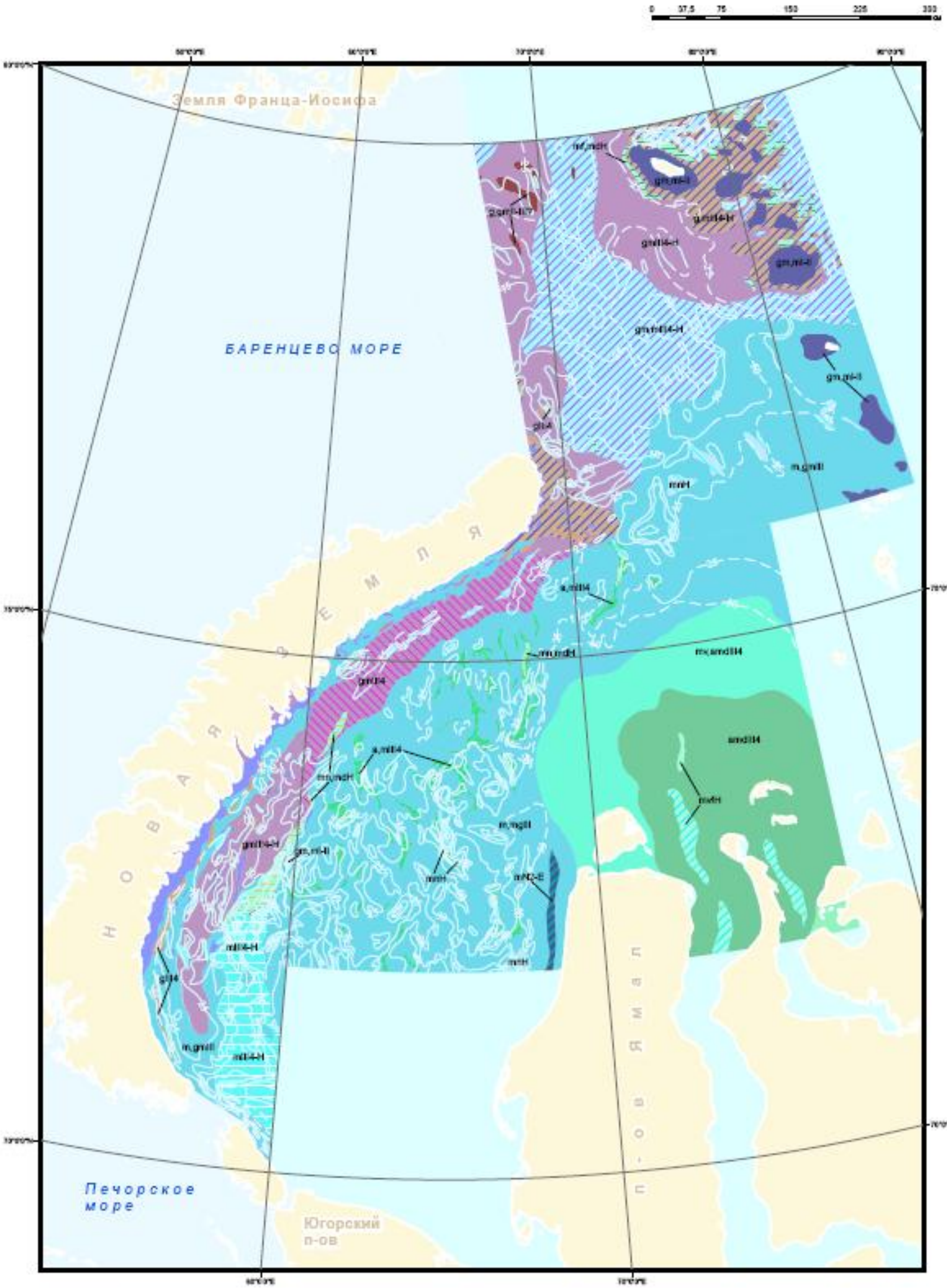

Fig. 6. Kara Sea. Map of Quaternary sediments.[12]

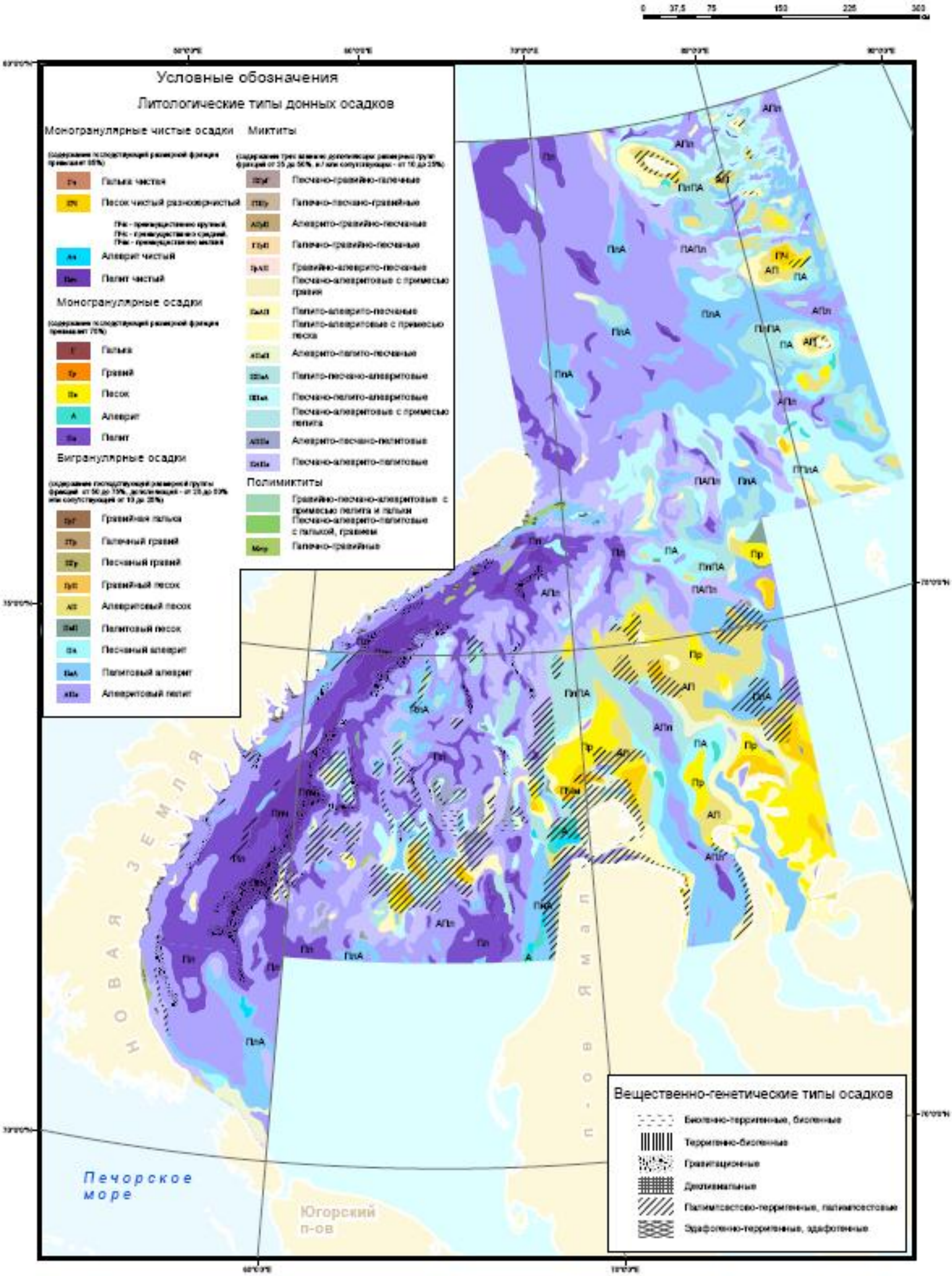

Fig. 7. Kara Sea. Lithological map of the bottom [12]

Chapter 2. Scenarios for the development of the Vikulovskaya field

2.1.Overview of Viculovskay.

The Vikulovskaya structure is located at a distance of 50 km from the coast of Novaya Zemlya in the bottom of the East Prinovozemelskoy depression. At a distance of 40 km to the northeast is a structure called University, which is the primary target for economic activity in the region. (Fig. 8)

Parameters of the Vikulovskaya structure:

The average water depth - 310 m

The area of the structure - 610 km^2

The form of deposits - elliptic; trap - anticline.

The average radius of the structure - 15 km

Depth of target layer - 2000 m

The effective height of producing formation - 10 m

Average porosity - 30%

The initial water saturation - 0.2

The absolute permeability - 500 mD

The oil volume factor - 1.2

Oil viscosity - 2 cp

Oil density - 800 kg/m^3

The initial reservoir pressure – 200 bar

The compressibility of the system-0.00116 1/bar

Initial gas content - 100 m^3/m^3

The gas volume factor [7] - 0.0075 m^3/m^3

Fig. 8. The positions the of Vikulovskoy and the University structures [17]

2.2. Recourses estimation

We are using formula (eq. 1) to calculate the volume of oil in place [8]:

$$N = \frac{\phi A(1 - S_i)h}{B} \tag{1}$$

ϕ – *porosity*

A – *area*

h – *effective height*

S_i – *initial water saturation*

B – *oil volume factor*

N – *oil in place*

We obtain 1.5 billion tons of oil or 1.875 billion cubic meters of oil in place.

2.3.Depletion drive (mode)

When modeling the depletion mode, the following assumptions in the reservoir model [6] were accepted:

- Bottom hole pressure - 1 MPa (the minimum possible pressure using a pump with gas separator)
- The well radius - 0.1 m
- Skin Factor - 1

The wells are vertical, placed evenly over the deposit. Of course, in reality during development of offshore hydrocarbon deposits in the Kara Sea horizontal wells will be applied, but for a basic estimation vertical wells with lack of imperfections in the degree of opening are the best option.

Use the following relations to obtain the profile of the recovery and evaluation of oil recovery ratio

Dyupii equation (eq.2)

$$q = \frac{2\pi kh(P - P_{wh})}{B\mu(\ln(\frac{R_k}{r_w}) + S - 0,75)} \tag{2}$$

$q -$ *flow rate*

$k -$ *permability*

$P -$ *reservoir pressure*

$P -$ *down hole pressure*

$\mu -$ *oil viscosity*

and the equation for the depletion mode (eq. 3):

$$q = -\frac{Nc}{B}\frac{dp}{dt} \tag{3}$$

$c -$ *oil compressibility*

Combining these two equations, the following result can be obtained (eq.4):

$$P = P_{wh} + (P_i - P_{wh})\exp(-\frac{NJ}{c}t) \tag{4}$$

$J -$ *well productivity*

When varying the number of productive wells in the field from 5 to 50 wells by step of 5, we obtain the following results:

1) In case of simultaneous entry of all wells see Tables 1-9; Figures. 9-11

Table 1 Production, 5 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m^3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
5	6233,258	1	19,73274	0,0221994	1918,02815	9590,1407	3356549	0,179016
5	6233,258	2	19,46924	0,0218871	1891,04863	9455,2431	6665884	0,355514
5	6233,258	3	19,20945	0,0215793	1864,44861	9322,2431	9928669	0,529529
5	6233,258	4	18,95331	0,0212757	1838,22276	9191,1138	13145559	0,701096
5	6233,258	5	18,70077	0,0209765	1812,36581	9061,829	16317199	0,870251
5	6233,258	6	18,45179	0,0206814	1786,87256	8934,3628	19444226	1,037025
5	6233,258	7	18,20631	0,0203905	1761,73792	8808,6896	22527268	1,201454
5	6233,258	8	17,96428	0,0201037	1736,95682	8684,7841	25566942	1,36357
5	6233,258	9	17,72565	0,0198209	1712,5243	8562,6215	28563860	1,523406
5	6233,258	10	17,49039	0,0195421	1688,43546	8442,1773	31518622	1,680993
5	6233,258	11	17,25843	0,0192672	1664,68546	8323,4273	34431821	1,836364
5	6233,258	12	17,02973	0,0189962	1641,26953	8206,3476	37304043	1,989549
5	6233,258	13	16,80425	0,018729	1618,18297	8090,9149	40135863	2,140579
5	6233,258	14	16,58195	0,0184655	1595,42116	7977,1058	42927850	2,289485
5	6233,258	15	16,36277	0,0182058	1572,97952	7864,8976	45680564	2,436297
5	6233,258	16	16,14667	0,0179497	1550,85356	7754,2678	48394558	2,581043
5	6233,258	17	15,93361	0,0176972	1529,03882	7645,1941	51070376	2,723753
5	6233,258	18	15,72355	0,0174483	1507,53093	7537,6547	53708555	2,864456
5	6233,258	19	15,51645	0,0172028	1486,32558	7431,6279	56309625	3,00318
5	6233,258	20	15,31225	0,0169609	1465,41851	7327,0926	58874107	3,139952
5	6233,258	21	15,11093	0,0167223	1444,80553	7224,0276	61402517	3,274801
5	6233,258	22	14,91245	0,0164871	1424,48249	7122,4125	63895361	3,407753
5	6233,258	23	14,71675	0,0162552	1404,44532	7022,2266	66353141	3,538834
5	6233,258	24	14,52381	0,0160265	1384,69001	6923,45	68776348	3,668072
5	6233,258	25	14,33358	0,0158011	1365,21257	6826,0629	71165470	3,795492

Table 2 Production, 10 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m^3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
10	4407,579	1	19,45101	0,0225742	1950,40913	19504,091	6826432	0,364076
10	4407,579	2	18,91789	0,0219219	1894,05377	18940,538	13455620	0,717633
10	4407,579	3	18,40016	0,0212885	1839,32674	18393,267	19893264	1,060974
10	4407,579	4	17,8974	0,0206734	1786,18101	17861,81	26144897	1,394395
10	4407,579	5	17,40917	0,0200761	1734,57088	17345,709	32215895	1,718181
10	4407,579	6	16,93504	0,019496	1684,45197	16844,52	38111477	2,032612
10	4407,579	7	16,47461	0,0189327	1635,78121	16357,812	43836711	2,337958
10	4407,579	8	16,02748	0,0183856	1588,51675	15885,167	49396520	2,634481
10	4407,579	9	15,59328	0,0178544	1542,61795	15426,179	54795683	2,922436
10	4407,579	10	15,17162	0,0173385	1498,04536	14980,454	60038842	3,202072
10	4407,579	11	14,76214	0,0168375	1454,76065	14547,606	65130504	3,473627
10	4407,579	12	14,3645	0,016351	1412,72662	14127,266	70075047	3,737336
10	4407,579	13	13,97834	0,0158786	1371,90712	13719,071	74876722	3,993425
10	4407,579	14	13,60334	0,0154198	1332,26707	13322,671	79539657	4,242115
10	4407,579	15	13,23918	0,0149742	1293,77238	12937,724	84067860	4,483619
10	4407,579	16	12,88554	0,0145416	1256,38996	12563,9	88465225	4,718145
10	4407,579	17	12,54212	0,0141214	1220,08767	12200,877	92735532	4,945895
10	4407,579	18	12,20862	0,0137134	1184,83431	11848,343	96882452	5,167064
10	4407,579	19	11,88476	0,0133171	1150,59956	11505,996	1,01E+08	5,381843
10	4407,579	20	11,57025	0,0129323	1117,354	11173,54	1,05E+08	5,590415
10	4407,579	21	11,26483	0,0125587	1085,06903	10850,69	1,09E+08	5,792962
10	4407,579	22	10,96824	0,0121958	1053,71692	10537,169	1,12E+08	5,989655
10	4407,579	23	10,68021	0,0118434	1023,27069	10232,707	1,16E+08	6,180666
10	4407,579	24	10,40051	0,0115012	993,704181	9937,0418	1,19E+08	6,366157
10	4407,579	25	10,12889	0,0111689	964,99197	9649,9197	1,23E+08	6,546289

Table 3. Production, 15 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m^3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
15	3598,773	1	19,16586	0,0226548	1957,37472	29360,621	10276217	0,548065
15	3598,773	2	18,36834	0,0216602	1871,44181	28071,627	20101287	1,072069
15	3598,773	3	17,60583	0,0207093	1789,28154	26839,223	29495015	1,573067
15	3598,773	4	16,8768	0,0198001	1710,72828	25660,924	38476338	2,052071
15	3598,773	5	16,17978	0,0189308	1635,62368	24534,355	47063363	2,510046
15	3598,773	6	15,51335	0,0180997	1563,81633	23457,245	55273398	2,947915
15	3598,773	7	14,87618	0,0173051	1495,16147	22427,422	63122996	3,36656
15	3598,773	8	14,26699	0,0165454	1429,5207	21442,811	70627980	3,766826
15	3598,773	9	13,68454	0,015819	1366,76171	20501,426	77803479	4,149519
15	3598,773	10	13,12766	0,0151245	1306,75797	19601,37	84663958	4,515411
15	3598,773	11	12,59523	0,0144605	1249,38852	18740,828	91223248	4,86524
15	3598,773	12	12,08618	0,0138257	1194,53771	17918,066	97494571	5,19971
15	3598,773	13	11,59947	0,0132187	1142,09497	17131,424	1,03E+08	5,519497
15	3598,773	14	11,13413	0,0126384	1091,95457	16379,319	1,09E+08	5,825244
15	3598,773	15	10,68922	0,0120835	1044,01545	15660,232	1,15E+08	6,117569
15	3598,773	16	10,26384	0,011553	998,180952	14972,714	1,2E+08	6,397059
15	3598,773	17	9,857142	0,0110458	954,358688	14315,38	1,25E+08	6,66428
15	3598,773	18	9,468295	0,0105609	912,460315	13686,905	1,3E+08	6,919769
15	3598,773	19	9,096519	0,0100972	872,401369	13086,021	1,34E+08	7,164041
15	3598,773	20	8,741064	0,0096539	834,101096	12511,516	1,39E+08	7,397589
15	3598,773	21	8,401215	0,0092301	797,482287	11962,234	1,43E+08	7,620884
15	3598,773	22	8,076286	0,0088249	762,471121	11437,067	1,47E+08	7,834376
15	3598,773	23	7,765622	0,0084375	728,997019	10934,955	1,51E+08	8,038495
15	3598,773	24	7,468597	0,008067	696,992502	10454,888	1,54E+08	8,233653
15	3598,773	25	7,184612	0,0077129	666,393051	9995,8958	1,58E+08	8,420243

Table 4. Production, 20 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m^3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
20	3116,629	1	18,87998	0,0226083	1953,35385	39067,077	13673477	0,729252
20	3116,629	2	17,82599	0,0212755	1838,20702	36764,14	26540926	1,415516
20	3116,629	3	16,83413	0,0200214	1729,8479	34596,958	38649861	2,061326
20	3116,629	4	15,90073	0,0188412	1627,87636	32557,527	50044996	2,669066
20	3116,629	5	15,02236	0,0177305	1531,91586	30638,317	60768407	3,240982
20	3116,629	6	14,19577	0,0166853	1441,61207	28832,241	70859692	3,779184
20	3116,629	7	13,4179	0,0157018	1356,63154	27132,631	80356112	4,285659
20	3116,629	8	12,68588	0,0147762	1276,66046	25533,209	89292735	4,762279
20	3116,629	9	11,99702	0,0139051	1201,40353	24028,071	97702560	5,210803
20	3116,629	10	11,34877	0,0130854	1130,58287	22611,657	1,06E+08	5,632887
20	3116,629	11	10,73872	0,0123141	1063,93697	21278,739	1,13E+08	6,030091
20	3116,629	12	10,16464	0,0115882	1001,21972	20024,394	1,2E+08	6,403879
20	3116,629	13	9,624404	0,0109051	942,199554	18843,991	1,27E+08	6,755634
20	3116,629	14	9,11601	0,0102623	886,65852	17733,17	1,33E+08	7,086653
20	3116,629	15	8,637585	0,0096573	834,391534	16687,831	1,39E+08	7,398159
20	3116,629	16	8,187363	0,009088	785,205597	15704,112	1,44E+08	7,691303
20	3116,629	17	7,76368	0,0085523	738,919086	14778,382	1,49E+08	7,967166
20	3116,629	18	7,364973	0,0080482	695,361084	13907,222	1,54E+08	8,226767
20	3116,629	19	6,989769	0,0075737	654,370751	13087,415	1,59E+08	8,471066
20	3116,629	20	6,636682	0,0071273	615,796728	12315,935	1,63E+08	8,700963
20	3116,629	21	6,30441	0,0067071	579,496576	11589,932	1,67E+08	8,917308
20	3116,629	22	5,991724	0,0063118	545,336256	10906,725	1,71E+08	9,120901
20	3116,629	23	5,69747	0,0059397	513,189627	10263,793	1,75E+08	9,312491
20	3116,629	24	5,420563	0,0055896	482,937987	9658,7597	1,78E+08	9,492788
20	3116,629	25	5,159978	0,0052601	454,469628	9089,3926	1,81E+08	9,662457

Table 5. Production, 25 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m^3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
25	2787,598	1	18,59473	0,0224901	1943,14285	48578,571	17002500	0,9068
25	2787,598	2	17,29339	0,0208267	1799,42456	44985,614	32747465	1,746531
25	2787,598	3	16,0883	0,0192863	1666,33592	41658,398	47327904	2,524155
25	2787,598	4	14,97234	0,0178598	1543,09076	38577,269	60829948	3,244264
25	2787,598	5	13,93892	0,0165389	1428,96103	35724,026	73333357	3,911112
25	2787,598	6	12,98194	0,0153157	1323,27253	33081,813	84911992	4,52864
25	2787,598	7	12,09573	0,0141829	1225,40095	30635,024	95634250	5,100493
25	2787,598	8	11,27507	0,0131339	1134,76812	28369,203	1,06E+08	5,630052
25	2787,598	9	10,51511	0,0121625	1050,83865	26270,966	1,15E+08	6,120443
25	2787,598	10	9,811356	0,0112629	973,11676	24327,919	1,23E+08	6,574564
25	2787,598	11	9,159652	0,0104299	901,143316	22528,583	1,31E+08	6,995098
25	2787,598	12	8,55615	0,0096585	834,493157	20862,329	1,38E+08	7,384528
25	2787,598	13	7,997284	0,0089441	772,772561	19319,314	1,45E+08	7,745155
25	2787,598	14	7,479752	0,0082826	715,616931	17890,423	1,51E+08	8,07911
25	2787,598	15	7,000498	0,00767	662,688632	16567,216	1,57E+08	8,388364
25	2787,598	16	6,556691	0,0071027	613,675004	15341,875	1,63E+08	8,674746
25	2787,598	17	6,145708	0,0065774	568,286511	14207,163	1,68E+08	8,939947
25	2787,598	18	5,765122	0,0060909	526,255032	13156,376	1,72E+08	9,185532
25	2787,598	19	5,412685	0,0056404	487,332276	12183,307	1,76E+08	9,412954
25	2787,598	20	5,086315	0,0052232	451,288315	11282,208	1,8E+08	9,623555
25	2787,598	21	4,784084	0,0048369	417,91023	10447,756	1,84E+08	9,81858
25	2787,598	22	4,504207	0,0044792	387,000848	9675,0212	1,87E+08	9,99918
25	2787,598	23	4,245029	0,0041479	358,377578	8959,4394	1,91E+08	10,16642
25	2787,598	24	4,005021	0,0038411	331,871336	8296,7834	1,94E+08	10,3213
25	2787,598	25	3,782764	0,003557	307,325543	7683,1386	1,96E+08	10,46472

Table 6. Production, 30 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m^3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
30	2544,717	1	18,3109	0,0223261	1928,97773	57869,332	20254266	1,080228
30	2544,717	2	16,77197	0,0203413	1757,49184	52724,755	38707930	2,064423
30	2544,717	3	15,36984	0,018533	1601,25104	48037,531	55521066	2,961124
30	2544,717	4	14,09236	0,0168854	1458,90002	43767,001	70839517	3,778108
30	2544,717	5	12,92845	0,0153843	1329,20399	39876,12	84796158	4,522462
30	2544,717	6	11,86802	0,0140166	1211,03792	36331,138	97512057	5,200643
30	2544,717	7	10,90185	0,0127706	1103,3768	33101,304	1,09E+08	5,818534
30	2544,717	8	10,02158	0,0116353	1005,28674	30158,602	1,2E+08	6,381495
30	2544,717	9	9,21956	0,0106009	915,91687	27477,506	1,29E+08	6,894408
30	2544,717	10	8,488842	0,0096585	834,491974	25034,759	1,38E+08	7,361724
30	2544,717	11	7,823085	0,0087998	760,30574	22809,172	1,46E+08	7,787495
30	2544,717	12	7,216513	0,0080175	692,714654	20781,44	1,53E+08	8,175415
30	2544,717	13	6,663866	0,0073048	631,132407	18933,972	1,6E+08	8,528849
30	2544,717	14	6,160349	0,0066554	575,024814	17250,744	1,66E+08	8,850863
30	2544,717	15	5,701595	0,0060637	523,90518	15717,155	1,71E+08	9,14425
30	2544,717	16	5,283623	0,0055247	477,330074	14319,902	1,76E+08	9,411555
30	2544,717	17	4,90281	0,0050335	434,89549	13046,865	1,81E+08	9,655096
30	2544,717	18	4,555851	0,004586	396,233334	11887	1,85E+08	9,876987
30	2544,717	19	4,239736	0,0041783	361,00824	10830,247	1,89E+08	10,07915
30	2544,717	20	3,951724	0,0038069	328,914652	9867,4396	1,92E+08	10,26334
30	2544,717	21	3,689316	0,0034685	299,67418	8990,2254	1,96E+08	10,43116
30	2544,717	22	3,450236	0,0031601	273,033183	8190,9955	1,98E+08	10,58406
30	2544,717	23	3,23241	0,0028792	248,760567	7462,817	2,01E+08	10,72337
30	2544,717	24	3,033949	0,0026232	226,645783	6799,3735	2,03E+08	10,85029
30	2544,717	25	2,853132	0,00239	206,497001	6194,91	2,06E+08	10,96593

Table 7. Production, 35 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m^3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
35	2355,95	1	18,02905	0,0221308	1912,0987	66923,455	23423209	1,249238
35	2355,95	2	16,26256	0,0198351	1713,74895	59981,213	44416634	2,368887
35	2355,95	3	14,67931	0,0177775	1535,97482	53759,119	63232325	3,372391
35	2355,95	4	13,2603	0,0159334	1376,64193	48182,467	80096189	4,271797
35	2355,95	5	11,98849	0,0142805	1233,83728	43184,305	95210696	5,077904
35	2355,95	6	10,84861	0,0127991	1105,84633	38704,622	1,09E+08	5,80039
35	2355,95	7	9,826974	0,0114714	991,132411	34689,634	1,21E+08	6,44793
35	2355,95	8	8,911317	0,0102815	888,318227	31091,138	1,32E+08	7,028298
35	2355,95	9	8,090644	0,0092149	796,169376	27865,928	1,42E+08	7,548462
35	2355,95	10	7,355102	0,008259	713,579498	24975,282	1,5E+08	8,014667
35	2355,95	11	6,695862	0,0074023	639,557004	22384,495	1,58E+08	8,432511
35	2355,95	12	6,105007	0,0066344	573,213162	20062,461	1,65E+08	8,80701
35	2355,95	13	5,575444	0,0059462	513,751437	17981,3	1,71E+08	9,142661
35	2355,95	14	5,100815	0,0053294	460,457917	16116,027	1,77E+08	9,443494
35	2355,95	15	4,67542	0,0047765	412,692751	14444,246	1,82E+08	9,71312
35	2355,95	16	4,294154	0,004281	369,882458	12945,886	1,87E+08	9,954776
35	2355,95	17	3,952438	0,003837	331,513051	11602,957	1,91E+08	10,17136
35	2355,95	18	3,64617	0,0034389	297,123858	10399,335	1,94E+08	10,36549
35	2355,95	19	3,371672	0,0030822	266,301996	9320,5699	1,98E+08	10,53947
35	2355,95	20	3,125649	0,0027625	238,67741	8353,7093	2,01E+08	10,69541
35	2355,95	21	2,905147	0,0024759	213,918434	7487,1452	2,03E+08	10,83517
35	2355,95	22	2,707518	0,0022191	191,727808	6710,4733	2,06E+08	10,96043
35	2355,95	23	2,53039	0,0019889	171,839105	6014,3687	2,08E+08	11,0727
35	2355,95	24	2,371637	0,0017826	154,013538	5390,4738	2,09E+08	11,17332
35	2355,95	25	2,229351	0,0015977	138,037089	4831,2981	2,11E+08	11,2635

Table 7. Production, 40 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m^3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
40	2203,789	1	17,74956	0,0219129	1893,27221	75730,888	26505811	1,413643
40	2203,789	2	15,76567	0,0193174	1669,02522	66761,009	49872164	2,659849
40	2203,789	3	14,01677	0,0170294	1471,33896	58853,559	70470909	3,758449
40	2203,789	4	12,47501	0,0150124	1297,06749	51882,7	88629854	4,726926
40	2203,789	5	11,11586	0,0132342	1143,43745	45737,498	1,05E+08	5,580692
40	2203,789	6	9,917695	0,0116667	1008,00399	40320,159	1,19E+08	6,333335
40	2203,789	7	8,861447	0,0102849	888,611824	35544,473	1,31E+08	6,996832
40	2203,789	8	7,930304	0,0090667	783,360963	31334,439	1,42E+08	7,581742
40	2203,789	9	7,10945	0,0079928	690,576449	27623,058	1,52E+08	8,097372
40	2203,789	10	6,385822	0,0070461	608,781717	24351,269	1,6E+08	8,551929
40	2203,789	11	5,747903	0,0062115	536,675092	21467,004	1,68E+08	8,952646
40	2203,789	12	5,185542	0,0054758	473,109073	18924,363	1,74E+08	9,305901
40	2203,789	13	4,689789	0,0048272	417,072077	16682,883	1,8E+08	9,617315
40	2203,789	14	4,252755	0,0042555	367,672335	14706,893	1,85E+08	9,891844
40	2203,789	15	3,867485	0,0037514	324,123702	12964,948	1,9E+08	10,13386
40	2203,789	16	3,527848	0,0033071	285,73315	11429,326	1,94E+08	10,3472
40	2203,789	17	3,228439	0,0029154	251,889733	10075,589	1,98E+08	10,53528
40	2203,789	18	2,964494	0,0025701	222,054871	8882,1948	2,01E+08	10,70108
40	2203,789	19	2,731811	0,0022657	195,753773	7830,1509	2,03E+08	10,84724
40	2203,789	20	2,526688	0,0019973	172,567886	6902,7155	2,06E+08	10,9761
40	2203,789	21	2,345861	0,0017607	152,128232	6085,1293	2,08E+08	11,08968
40	2203,789	22	2,186452	0,0015522	134,109535	5364,3814	2,1E+08	11,18982
40	2203,789	23	2,045923	0,0013683	118,225047	4729,0019	2,11E+08	11,27809
40	2203,789	24	1,92204	0,0012063	104,221983	4168,8793	2,13E+08	11,35591
40	2203,789	25	1,81283	0,0010634	91,8775	3675,1	2,14E+08	11,42452

Table 8. Production, 45 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m^3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
45	2077,753	1	17,47271	0,0216783	1873,00832	84285,374	29499881	1,573327
45	2077,753	2	15,28159	0,0187948	1623,86954	73074,129	55075826	2,937377
45	2077,753	3	13,38192	0,0162948	1407,87004	63354,152	77249779	4,119988
45	2077,753	4	11,73493	0,0141273	1220,60177	54927,08	96474257	5,145294
45	2077,753	5	10,30702	0,0122482	1058,24305	47620,937	1,13E+08	6,034218
45	2077,753	6	9,069046	0,010619	917,480531	41286,624	1,28E+08	6,804902
45	2077,753	7	7,995739	0,0092065	795,441577	35794,871	1,4E+08	7,473072
45	2077,753	8	7,065199	0,0079819	689,635672	31033,605	1,51E+08	8,052366
45	2077,753	9	6,258435	0,0069202	597,903571	26905,661	1,6E+08	8,554605
45	2077,753	10	5,558982	0,0059997	518,373245	23326,796	1,69E+08	8,990039
45	2077,753	11	4,952568	0,0052016	449,421669	20223,975	1,76E+08	9,367553
45	2077,753	12	4,426816	0,0045097	389,641708	17533,877	1,82E+08	9,694852
45	2077,753	13	3,970997	0,0039099	337,813397	15201,603	1,87E+08	9,978615
45	2077,753	14	3,575809	0,0033898	292,879044	13179,557	1,92E+08	10,22463
45	2077,753	15	3,233187	0,0029389	253,921648	11426,474	1,96E+08	10,43793
45	2077,753	16	2,936139	0,002548	220,146183	9906,5782	1,99E+08	10,62285
45	2077,753	17	2,678603	0,0022091	190,863371	8588,8517	2,02E+08	10,78318
45	2077,753	18	2,455323	0,0019152	165,475621	7446,4029	2,05E+08	10,92218
45	2077,753	19	2,261743	0,0016605	143,46483	6455,9174	2,07E+08	11,04269
45	2077,753	20	2,093912	0,0014396	124,381812	5597,1815	2,09E+08	11,14717
45	2077,753	21	1,948405	0,0012481	107,837127	4852,6707	2,11E+08	11,23775
45	2077,753	22	1,822252	0,0010821	93,4931387	4207,1912	2,12E+08	11,31628
45	2077,753	23	1,71288	0,0009382	81,0571202	3647,5704	2,13E+08	11,38437
45	2077,753	24	1,618056	0,0008134	70,2752825	3162,3877	2,15E+08	11,4434
45	2077,753	25	1,535845	0,0007052	60,9275943	2741,7417	2,16E+08	11,49458

Table 9. Production, 50 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m^3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
50	1971,129	1	17,19871	0,0214313	1851,66529	92583,265	32404143	1,728221
50	1971,129	2	14,81043	0,0182716	1578,66242	78933,121	60030735	3,201639
50	1971,129	3	12,77427	0,0155777	1345,9101	67295,505	83584162	4,457822
50	1971,129	4	11,03831	0,0132809	1147,47396	57373,698	1,04E+08	5,528798
50	1971,129	5	9,5583	0,0113229	978,29452	48914,726	1,21E+08	6,441873
50	1971,129	6	8,296495	0,0096535	834,058292	41702,915	1,35E+08	7,220327
50	1971,129	7	7,220726	0,0082302	711,087735	35554,387	1,48E+08	7,884009
50	1971,129	8	6,303565	0,0070168	606,247515	30312,376	1,58E+08	8,44984
50	1971,129	9	5,521626	0,0059822	516,86456	25843,228	1,67E+08	8,932247
50	1971,129	10	4,854974	0,0051002	440,659907	22032,995	1,75E+08	9,343529
50	1971,129	11	4,28661	0,0043483	375,690594	18784,53	1,82E+08	9,694174
50	1971,129	12	3,802044	0,0037072	320,300123	16015,006	1,87E+08	9,993121
50	1971,129	13	3,388921	0,0031606	273,076224	13653,811	1,92E+08	10,24799
50	1971,129	14	3,036707	0,0026946	232,814847	11640,742	1,96E+08	10,46529
50	1971,129	15	2,736422	0,0022973	198,489463	9924,4731	2E+08	10,65054
50	1971,129	16	2,48041	0,0019586	169,22489	8461,2445	2,03E+08	10,80849
50	1971,129	17	2,262144	0,0016698	144,27498	7213,749	2,05E+08	10,94314
50	1971,129	18	2,076058	0,0014237	123,003596	6150,1798	2,07E+08	11,05795
50	1971,129	19	1,917408	0,0012138	104,868388	5243,4194	2,09E+08	11,15582
50	1971,129	20	1,782149	0,0010348	89,4069695	4470,3485	2,11E+08	11,23927
50	1971,129	21	1,666831	0,0008822	76,2251272	3811,2564	2,12E+08	11,31041
50	1971,129	22	1,568516	0,0007522	64,9867684	3249,3384	2,13E+08	11,37107
50	1971,129	23	1,484696	0,0006413	55,4053529	2770,2676	2,14E+08	11,42278
50	1971,129	24	1,413234	0,0005467	47,2365868	2361,8293	2,15E+08	11,46687
50	1971,129	25	1,352309	0,0004661	40,2721942	2013,6097	2,16E+08	11,50445

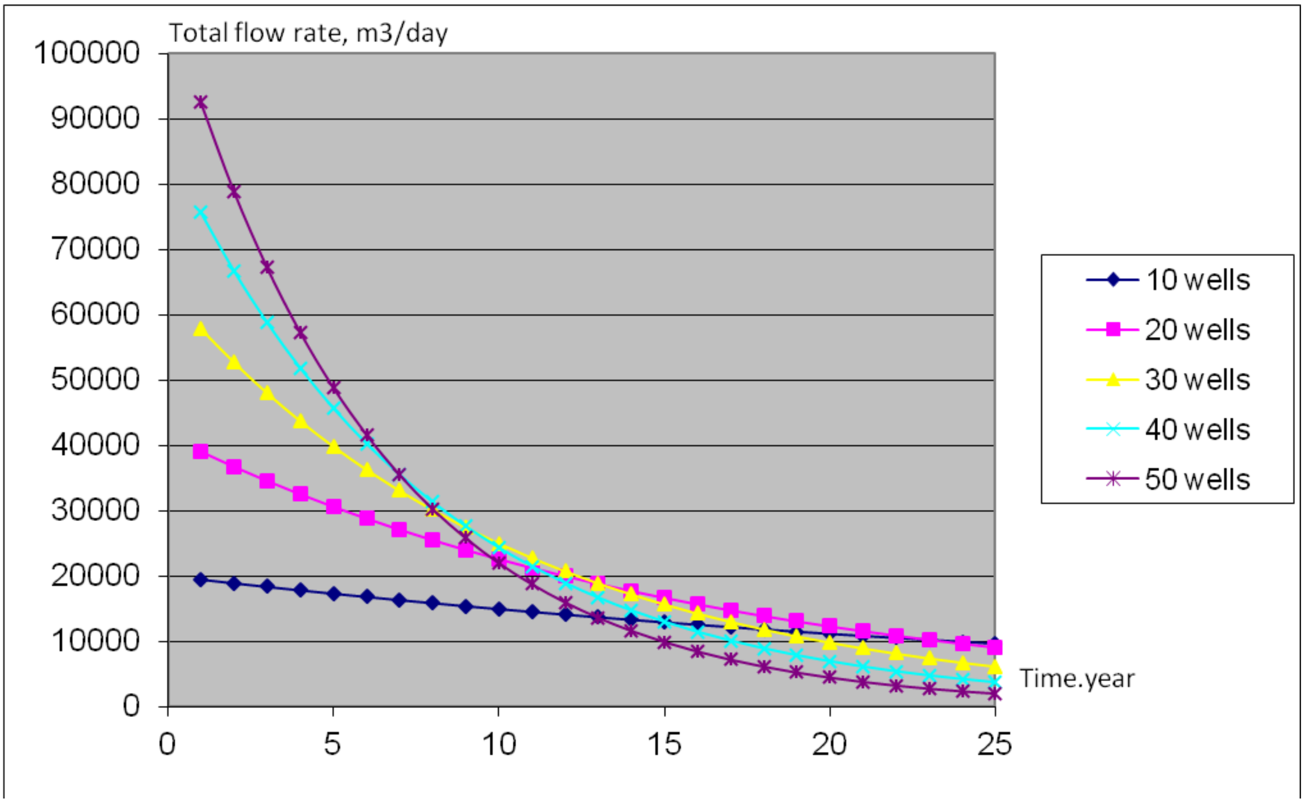

Fig. 9. Total flow rate vs. recovery time

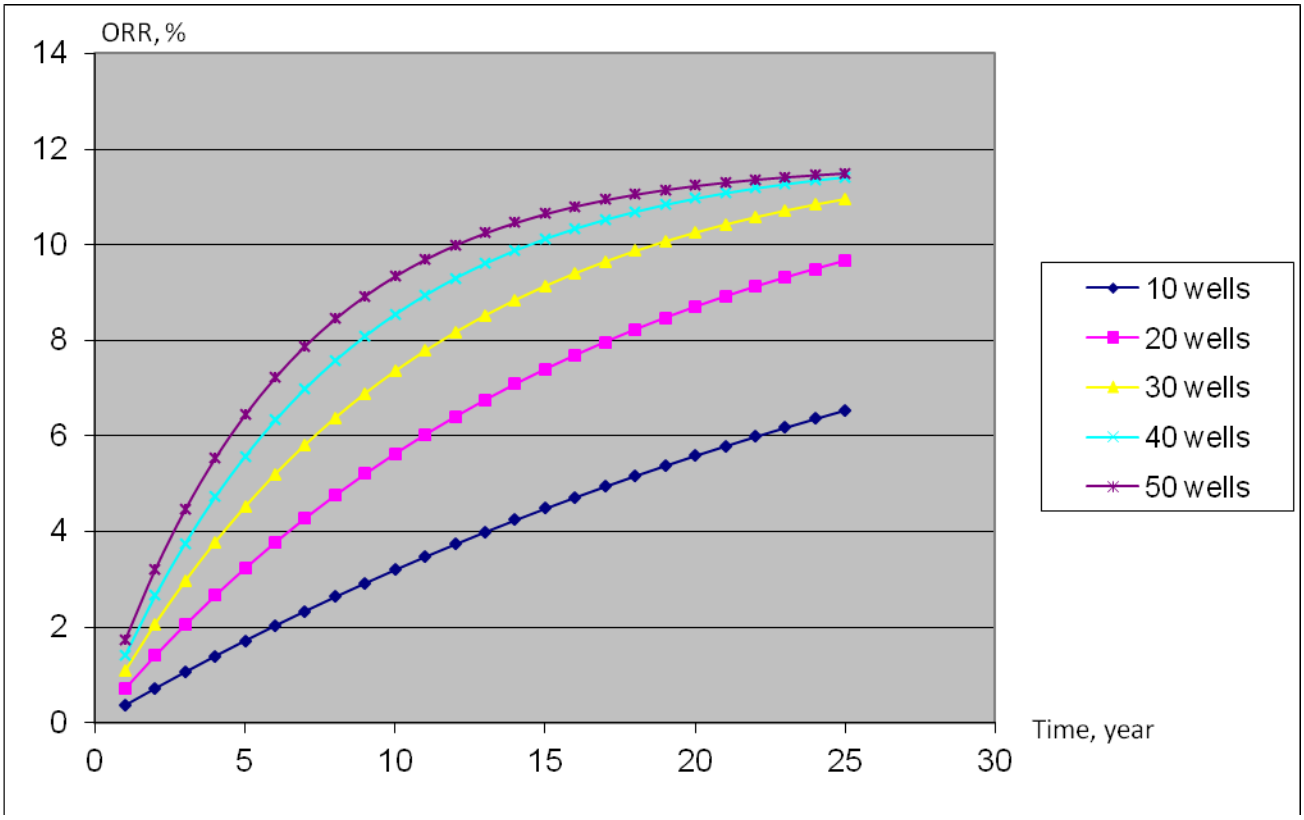

Fig. 10. ORR vs. recovery time (ORR, overall recovery rate)

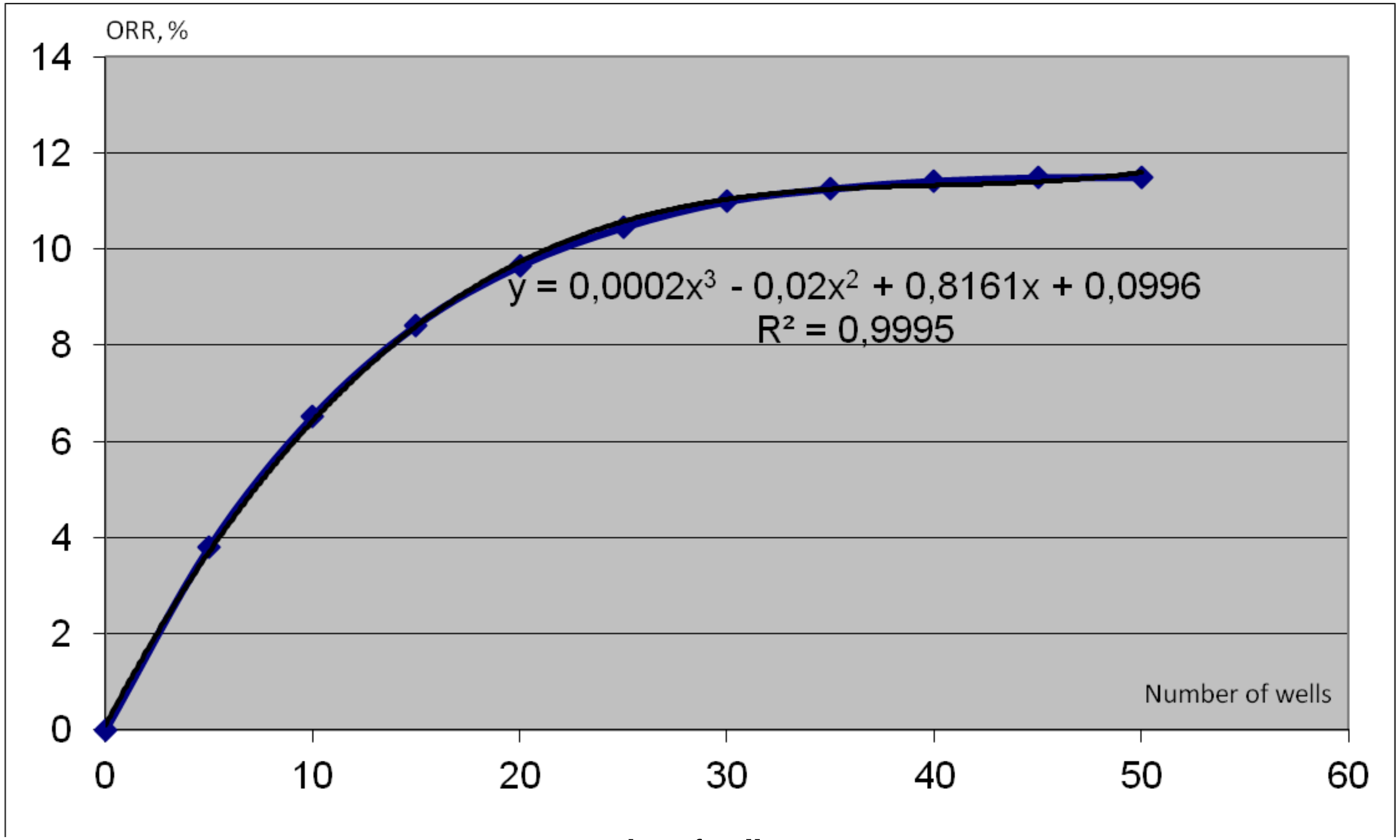

Fig. 11. ORR vs. number of wells. Recovery time is 25 years.

2) Entering no more than 5 wells per year (the realistic situation when drilling with 2 rigs) (Tables 10-12; Figure 12). Figures 13 and 14 show the number of wells in the optimal scenario vs. recovery time and the recovery profile.

Table 10 Production scenario, drilling with 2 rigs. 10 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
5	4407,579	1	19,45101	0,022574	1950,409127	9752,046	3413216	0,182038
10	4407,579	2	18,91789	0,021922	1894,053766	18940,54	10042404	0,535595
10	4407,579	3	18,40016	0,021289	1839,326744	18393,27	16480048	0,878936
10	4407,579	4	17,8974	0,020673	1786,181011	17861,81	22731681	1,212356
10	4407,579	5	17,40917	0,020076	1734,570877	17345,71	28802679	1,536143
10	4407,579	6	16,93504	0,019496	1684,451973	16844,52	34698261	1,850574
10	4407,579	7	16,47461	0,018933	1635,781211	16357,81	40423496	2,15592
10	4407,579	8	16,02748	0,018386	1588,516747	15885,17	45983304	2,452443
10	4407,579	9	15,59328	0,017854	1542,617949	15426,18	51382467	2,740398
10	4407,579	10	15,17162	0,017338	1498,045356	14980,45	56625626	3,020033
10	4407,579	11	14,76214	0,016838	1454,76065	14547,61	61717288	3,291589
10	4407,579	12	14,3645	0,016351	1412,726617	14127,27	66661831	3,555298
10	4407,579	13	13,97834	0,015879	1371,90712	13719,07	71463506	3,811387
10	4407,579	14	13,60334	0,01542	1332,267067	13322,67	76126441	4,060077
10	4407,579	15	13,23918	0,014974	1293,772379	12937,72	80654644	4,301581
10	4407,579	16	12,88554	0,014542	1256,38996	12563,9	85052009	4,536107
10	4407,579	17	12,54212	0,014121	1220,087674	12200,88	89322316	4,763857
10	4407,579	18	12,20862	0,013713	1184,834311	11848,34	93469236	4,985026
10	4407,579	19	11,88476	0,013317	1150,599563	11506	97496334	5,199805
10	4407,579	20	11,57025	0,012932	1117,353998	11173,54	1,01E+08	5,408377
10	4407,579	21	11,26483	0,012559	1085,069034	10850,69	1,05E+08	5,610923
10	4407,579	22	10,96824	0,012196	1053,716916	10537,17	1,09E+08	5,807617
10	4407,579	23	10,68021	0,011843	1023,27069	10232,71	1,12E+08	5,998628
10	4407,579	24	10,40051	0,011501	993,7041807	9937,042	1,16E+08	6,184119
10	4407,579	25	10,12889	0,011169	964,9919699	9649,92	1,19E+08	6,364251

Table 11 Production scenario, drilling with 2 rigs.20 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
5	3116,629	1	18,87998	0,022608	1953,353853	9766,769	3418369	0,182313
10	3116,629	2	17,82599	0,021276	1838,207023	18382,07	9852094	0,525445
15	3116,629	3	16,83413	0,020021	1729,8479	25947,72	18933795	1,009802
20	3116,629	4	15,90073	0,018841	1627,876359	32557,53	30328930	1,617543
20	3116,629	5	15,02236	0,017731	1531,915865	30638,32	41052341	2,189458
20	3116,629	6	14,19577	0,016685	1441,612075	28832,24	51143625	2,72766
20	3116,629	7	13,4179	0,015702	1356,631537	27132,63	60640046	3,234136
20	3116,629	8	12,68588	0,014776	1276,660456	25533,21	69576669	3,710756
20	3116,629	9	11,99702	0,013905	1201,403531	24028,07	77986494	4,15928
20	3116,629	10	11,34877	0,013085	1130,582871	22611,66	85900574	4,581364
20	3116,629	11	10,73872	0,012314	1063,936967	21278,74	93348133	4,978567
20	3116,629	12	10,16464	0,011588	1001,219724	20024,39	1E+08	5,352356
20	3116,629	13	9,624404	0,010905	942,1995535	18843,99	1,07E+08	5,70411
20	3116,629	14	9,11601	0,010262	886,6585201	17733,17	1,13E+08	6,035129
20	3116,629	15	8,637585	0,009657	834,3915345	16687,83	1,19E+08	6,346636
20	3116,629	16	8,187363	0,009088	785,2055972	15704,11	1,24E+08	6,639779
20	3116,629	17	7,76368	0,008552	738,9190859	14778,38	1,3E+08	6,915642
20	3116,629	18	7,364973	0,008048	695,3610843	13907,22	1,35E+08	7,175244
20	3116,629	19	6,989769	0,007574	654,3707515	13087,42	1,39E+08	7,419542
20	3116,629	20	6,636682	0,007127	615,7967279	12315,93	1,43E+08	7,64944
20	3116,629	21	6,30441	0,006707	579,4965763	11589,93	1,47E+08	7,865785
20	3116,629	22	5,991724	0,006312	545,3362558	10906,73	1,51E+08	8,069377
20	3116,629	23	5,69747	0,00594	513,1896271	10263,79	1,55E+08	8,260968
20	3116,629	24	5,420563	0,00559	482,9379865	9658,76	1,58E+08	8,441265
20	3116,629	25	5,159978	0,00526	454,4696278	9089,393	1,61E+08	8,610933

Table 12 Production scenario, drilling with 2 rigs. 30 wells

Number of wells	Drainage radius, m	Time, year	Pressure, MPa	Well flow rate, m3/sec	Well flow rate, m3/day	Total flow rate, m3/day	Accumulated recovery, m^3	ORR %
5	2544,717	1	18,3109	0,022326	1928,977726	9644,889	3375711	0,180038
10	2544,717	2	16,77197	0,020341	1757,491845	17574,92	9526932	0,508103
15	2544,717	3	15,36984	0,018533	1601,251038	24018,77	17933500	0,956453
20	2544,717	4	14,09236	0,016885	1458,900019	29178	28145801	1,501109
25	2544,717	5	12,92845	0,015384	1329,203988	33230,1	39776335	2,121405
30	2544,717	6	11,86802	0,014017	1211,037918	36331,14	52492234	2,799586
30	2544,717	7	10,90185	0,012771	1103,376797	33101,3	64077690	3,417477
30	2544,717	8	10,02158	0,011635	1005,286736	30158,6	74633201	3,980437
30	2544,717	9	9,21956	0,010601	915,9168698	27477,51	84250328	4,493351
30	2544,717	10	8,488842	0,009658	834,4919735	25034,76	93012494	4,960666
30	2544,717	11	7,823085	0,0088	760,3057404	22809,17	1,01E+08	5,386438
30	2544,717	12	7,216513	0,008018	692,7146542	20781,44	1,08E+08	5,774358
30	2544,717	13	6,663866	0,007305	631,1324073	18933,97	1,15E+08	6,127792
30	2544,717	14	6,160349	0,006655	575,0248144	17250,74	1,21E+08	6,449806
30	2544,717	15	5,701595	0,006064	523,9051796	15717,16	1,26E+08	6,743193
30	2544,717	16	5,283623	0,005525	477,330074	14319,9	1,31E+08	7,010498
30	2544,717	17	4,90281	0,005034	434,8954896	13046,86	1,36E+08	7,254039
30	2544,717	18	4,555851	0,004586	396,2333344	11887	1,4E+08	7,47593
30	2544,717	19	4,239736	0,004178	361,00824	10830,25	1,44E+08	7,678094
30	2544,717	20	3,951724	0,003807	328,9146522	9867,44	1,47E+08	7,862286
30	2544,717	21	3,689316	0,003468	299,6741803	8990,225	1,51E+08	8,030104
30	2544,717	22	3,450236	0,00316	273,0331828	8190,995	1,53E+08	8,183003
30	2544,717	23	3,23241	0,002879	248,7605667	7462,817	1,56E+08	8,322309
30	2544,717	24	3,033949	0,002623	226,6457831	6799,373	1,58E+08	8,44923
30	2544,717	25	2,853132	0,00239	206,4970011	6194,91	1,61E+08	8,564868

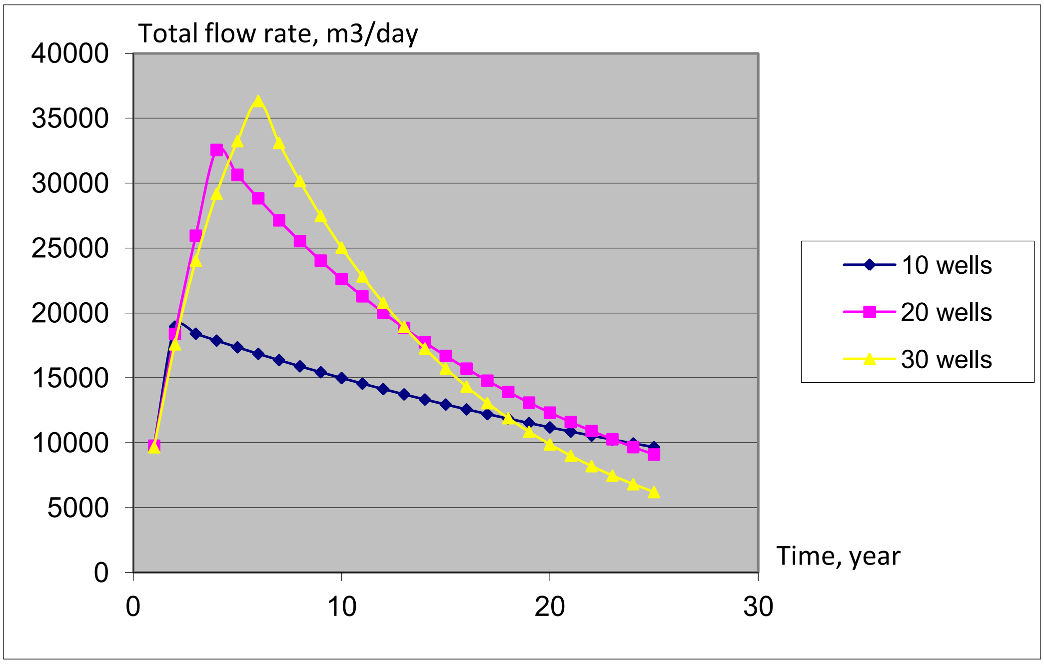

Fig. 12. Total flow rate vs. recovery time. (5 wells per year)

Year of exploitation	Number of wells	Flow rate, m^3/day	Year of exploitation	Number of wells	Flow rate, m^3/day
1	3	5786,933	**24**	30	18004,27
2	6	11059,41	**25**	30	16403,69
3	9	15863,16	**26**	30	14380,99
4	12	20239,86	**27**	30	12538,1
5	15	24227,47	**28**	30	10859,05
6	15	22073,65	**29**	30	9329,261
7	15	20111,31	**30**	30	7935,472
8	15	18323,42	**31**	30	7230,01
9	15	16694,47	**32**	30	6587,263
10	15	15210,33	**33**	30	6001,656
11	15	13858,13	**34**	30	5468,11
12	18	18413,08	**35**	30	4981,995
13	21	22563,09	**36**	30	4539,097
14	24	26344,17	**37**	30	3571,153
15	24	24002,18	**38**	30	2689,26
16	24	21868,39	**39**	30	1885,766
17	24	19924,29	**40**	30	1718,122
18	24	18153,02	**41**	30	1565,381
19	27	22326,15	**42**	30	1426,219
20	30	26128,3	**43**	30	1299,428
21	30	23805,49	**44**	30	619,491
22	30	21689,19	**45**	30	587460,3
23	30	19761,02			

Table 13. Optimal scenario

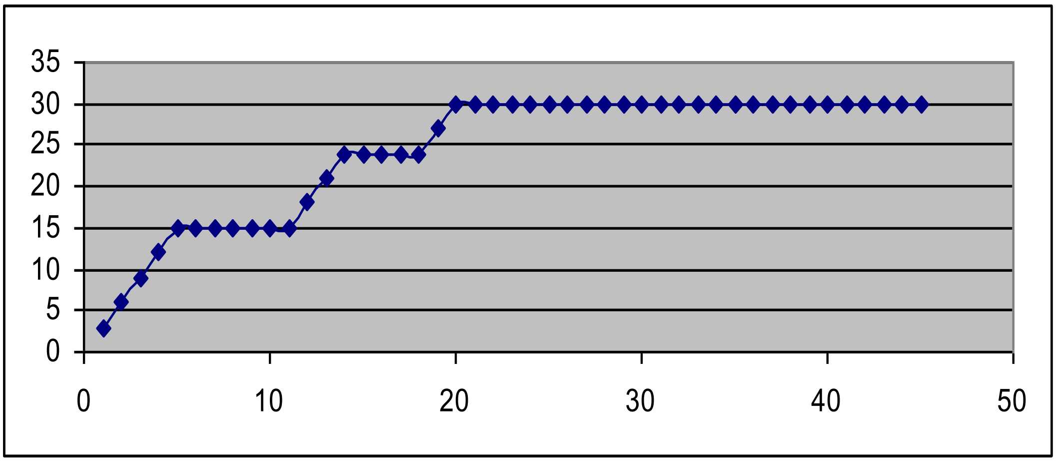

Fig. 13. Number of wells in the optimal scenario vs. recovery time

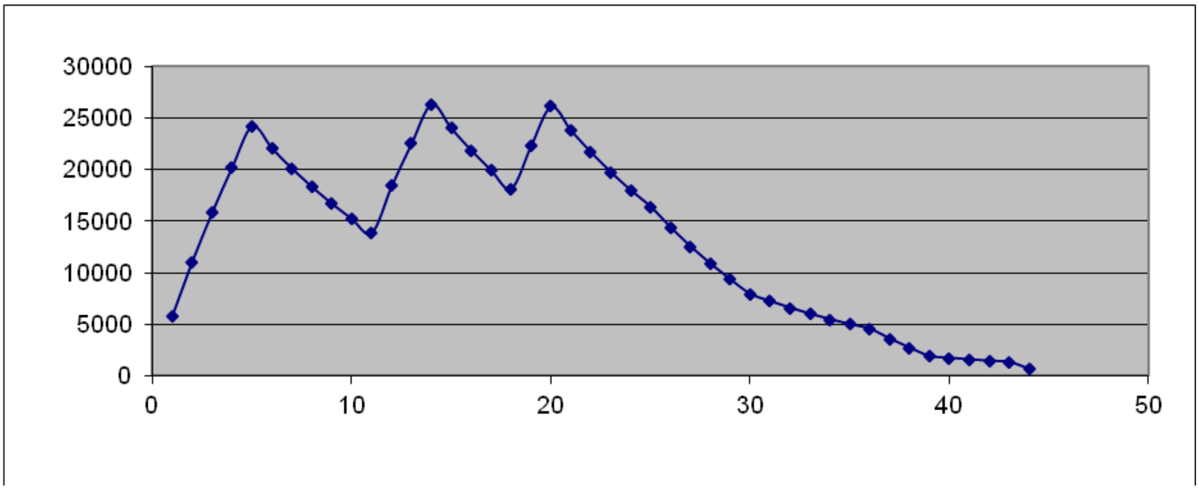

Fig. 14 Recovery profile non-processed

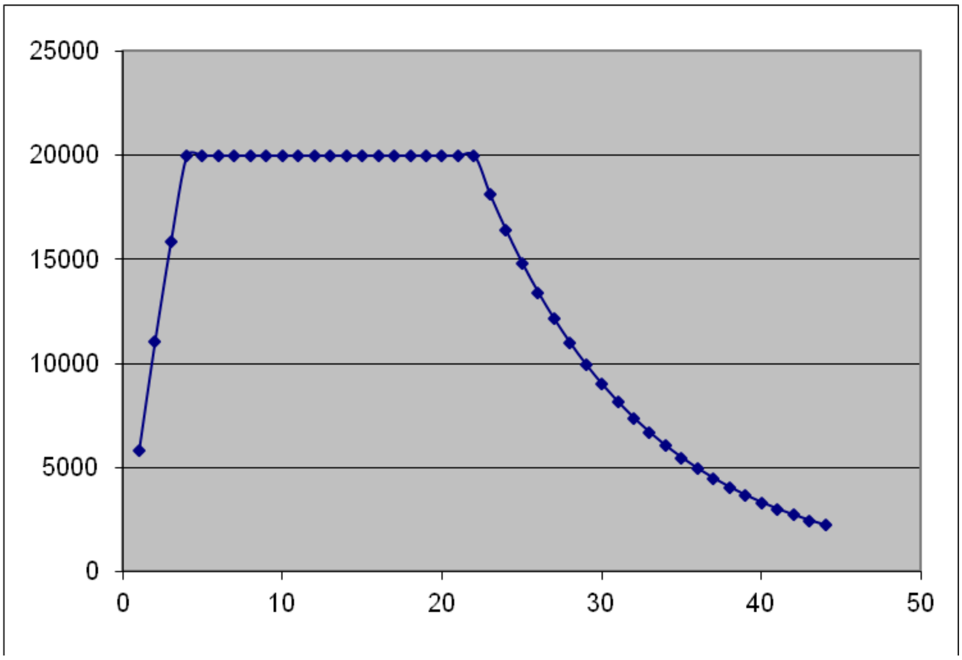

Fig.15 Recovery profile in depletion mode

Finally, under the primary drive of operation in the Vikulovskaya structure, the recovery factor is 11% and the~~,~~ oil rate production on the "plateau" - 20,000 m^3/day. (Fig. 15)

2.4. Water flooding

When modeling the flooding drive, the following assumptions are made in the model of a piston displacement:

Adopted for marginal flood.

Applied to horizontal wells, which form three contours (Fig. 16). Flow rate from all the wells are equal, and may change over time. Oil viscosity is 2 cp, water viscosity is 1 cp. The maximum pressure in the injection wells downhole is 450 bar.

If water break occurs in the first contour of wells, they are transferred to injectors.

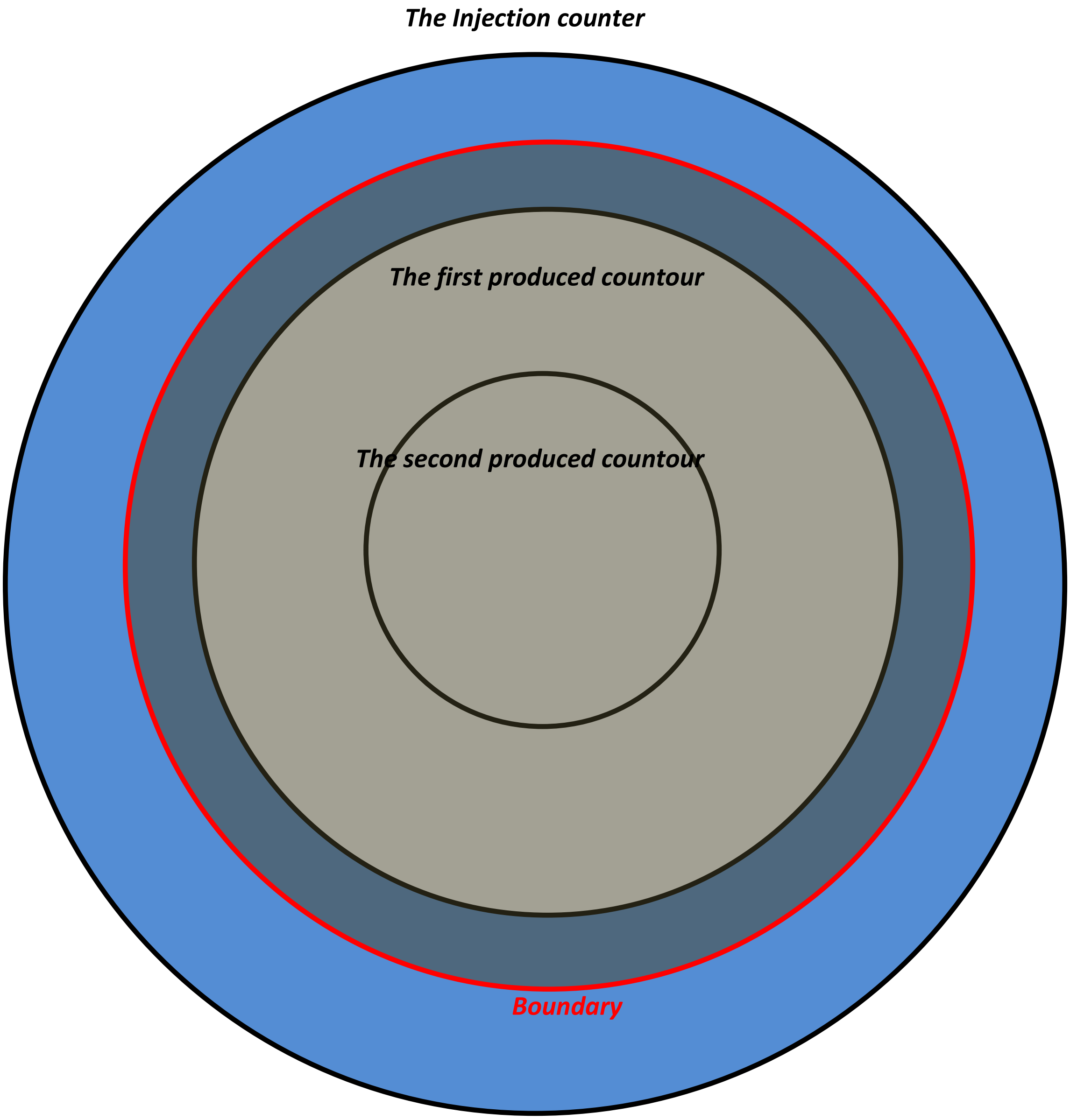

Fig. 16. Schematic diagram of the water flooding

In the injection contour - 20 wells; in the first production row – 14; in the second row- 6. The length of the horizontal well is 2 km.

The expression for the determination of the interface between oil and water (eq.5):

$$R_k = \sqrt{R_1^2 - \frac{\sum Qt}{2\pi\phi}} \quad (5)$$

$$Qt - accumulated\ injection$$

The solution for a given system under given constraints is found from equation 6:

$$P_1 - P_3 = \frac{QB\mu_w \ln(\frac{R_1}{R_k})}{2\pi kh} + \frac{1}{3}\frac{QB\mu_o \ln(\frac{R_2}{R_3})}{2\pi kh} + \frac{QB\mu_o \ln(\frac{R_k}{R_2})}{2\pi kh} \quad (6)$$

$$Q - total\ oil\ flow\ rate$$

$$P_1 - P_3 - depression$$

If we solve this equation relative to Q, we will get the dependence between Q and t. Model ORR is equal the relationship between cumulative production and reserves

The real oil recovery rate (ORR) is obtained by multiplying the model ORR by 0.8. The first approximation takes into account the heterogeneity and residual oil behind the front. Water breakthrough in the first row of wells is highlighted in blue.

Assume R1 = 15 km, R2 = 10 km and R3 = 5 km, we obtain the following characteristics of the development (Table 14, Figures 17-18):

Table 14 Oil recovery rate, . R1 = 15 km, R2 = 10 km and R3 = 5 km

Year	Accumulated injection, ton	Boundary, km	Flow rate, m3/sec	Flow rate, m3/day	Total Flow rate, m3/day	Annual flow rate m3/year	ORR %	Real ORR %
1	0	15	0,616639848	1775,922762	53277,68287	18647189	0	0
2	18647189	14,66636769	0,627731283	1807,866095	54235,98284	18982593,99	3,107864834	2,486291867
3	37629783	14,31875185	0,640007497	1843,221592	55296,64776	19353826,72	6,2716305	5,0173044
4	56983609,71	13,95542628	0,653705505	1882,671855	56480,15566	19768054,48	9,497268286	7,597814628
5	76751664,19	13,57428911	0,669135431	1927,110043	57813,30128	20234655,45	12,79194403	10,23355523
6	96986319,64	13,17273934	0,686712473	1977,731921	59331,95763	20766185,17	16,16438661	12,93150929
7	117752504,8	12,74749664	0,707007815	2036,182506	61085,47519	21379916,32	19,62541747	15,70033397
8	139132421,1	12,29432876	0,730833395	2104,800178	63144,00534	22100401,87	23,18873685	18,55098948
9	161232823	11,80762234	0,759390747	2187,045352	65611,36057	22963976,2	26,87213717	21,49770973
10	184196799,2	11,27967191	0,79455026	2288,304749	68649,14246	24027199,86	30,69946653	24,55957323
11	208223999,1	10,69942557	0,839421195	2417,533042	72525,99126	25384096,94	34,70399984	27,76319987
12	233608096	10,05008434	0,899652463	2590,999095	77729,97284	27205490,49	38,93468267	31,14774613
13	260813586,5	9,303973009	1,132515607	3261,644948	97849,34845	34247271,96	43,46893108	34,77514487
14	295060858,4	8,269580173	1,132515607	3261,644948	97849,34845	34247271,96	49,17680974	39,34144779
15	329308130,4	7,085760278	1,132515607	3261,644948	97849,34845	34247271,96	54,8846884	43,90775072
16	363555402,4	5,659508919	1,132515607	3261,644948	97849,34845	34247271,96	60,59256706	48,47405365
17	397802674,3	3,721838752	1,132515607	3261,644948	97849,34845	34247271,96	66,30044572	53,04035658

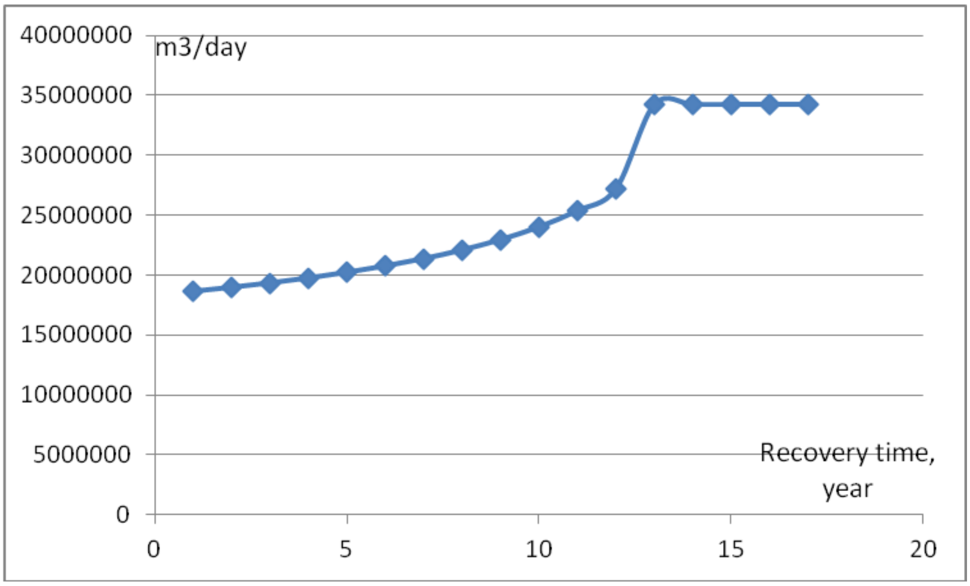

Fig. 17. Total flow rate vs. recovery time

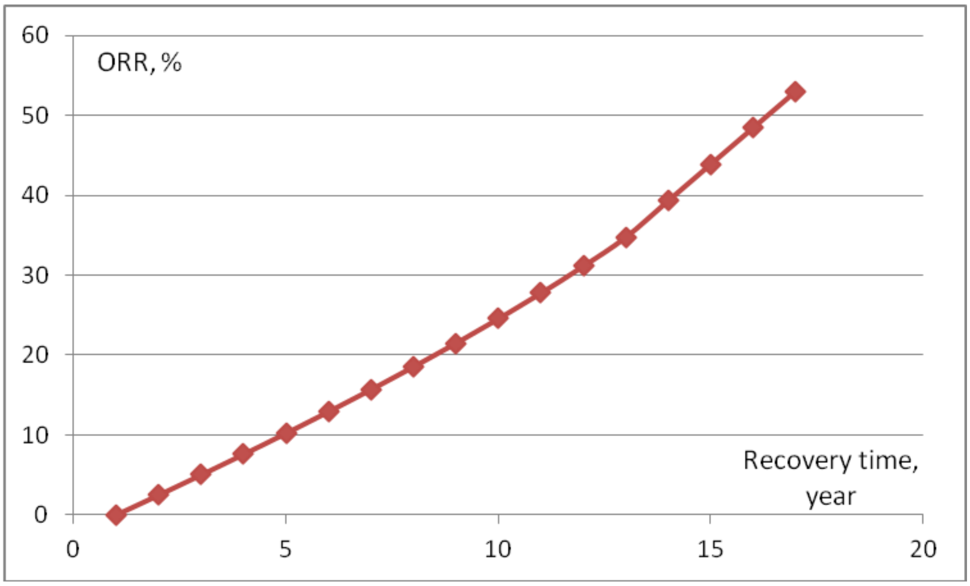

Fig. 18. The real ORR vs. recovery time

Assume R1 = 12,5 km, R2 = 10 km and R3 = 3 km, we obtain the following characteristics of development (Table 15, Fig. 19-20):

Table 15 Oil recovery rate, . R1 = 12,5 km, R2 = 10 km and R3 = 3 km

Year	**Accumulated injection, ton**	**Boundary, km**	**Flow rate, m3/sec**	**Flow rate, m3/day**	**Total Flow rate, m3/day**	**Annual flow rate m3/year**	**ORR %**	**Real ORR %**
1	0	12,5	0,628535191	1810,181349	54305,44048	19006904,17	0	0
2	19006904,17	12,08972331	0,645791412	1859,879268	55796,37803	19528732,31	3,801380834	3,041104667
3	38535636,48	11,65314724	0,665940897	1917,909784	57537,29353	20138052,74	7,707127296	6,165701837
4	58673689,22	11,18511747	0,689933333	1987,007998	59610,23994	20863583,98	11,73473784	9,387790275
5	79537273,2	10,67861244	0,719226784	2071,373137	62141,19411	21749417,94	15,90745464	12,72596371
6	101286691,1	10,12365975	0,756202138	2177,862157	65335,8647	22867552,65	20,25733823	16,20587058
7	124154243,8	9,505299567	0,652008083	1877,783279	56333,49836	19716724,43	24,83084876	19,864679
8	143870968,2	8,937861444	0,652008083	1877,783279	56333,49836	19716724,43	28,77419364	23,01935491
9	163587692,6	8,331867409	0,652008083	1877,783279	56333,49836	19716724,43	32,71753853	26,17403082
10	183304417,1	7,678193919	0,652008083	1877,783279	56333,49836	19716724,43	36,66088341	29,32870673
11	203021141,5	6,963426541	0,652008083	1877,783279	56333,49836	19716724,43	40,6042283	32,48338264
12	222737865,9	6,166356827	0,652008083	1877,783279	56333,49836	19716724,43	44,54757318	35,63805855
13	242454590,3	5,249628925	0,652008083	1877,783279	56333,49836	19716724,43	48,49091807	38,79273445
14	262171314,8	4,134398528	0,652008083	1877,783279	56333,49836	19716724,43	52,43426295	41,94741036
15	281888039,2	2,574470532	0,652008083	1877,783279	56333,49836	19716724,43	56,37760784	45,10208627

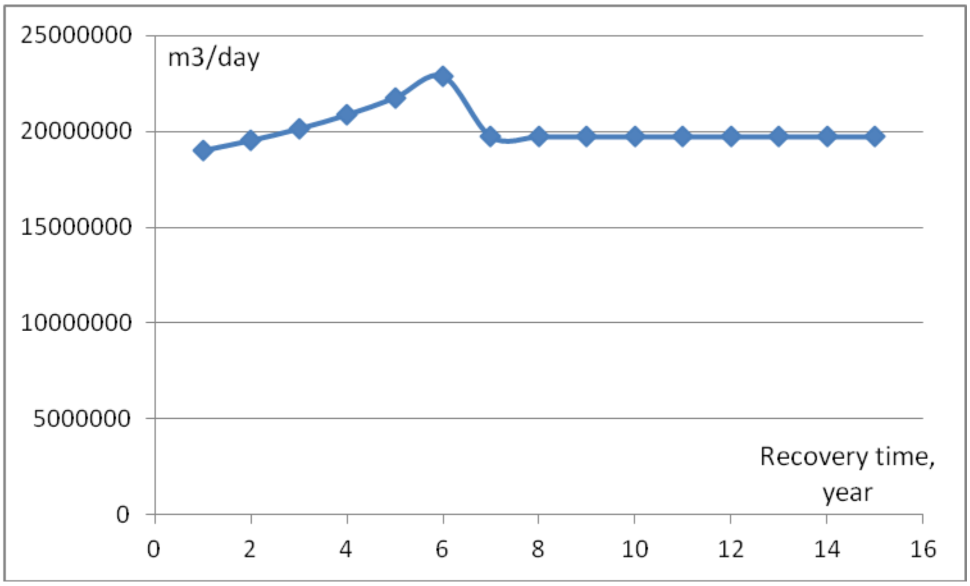

Fig. 19. Total flow rate vs. recovery time

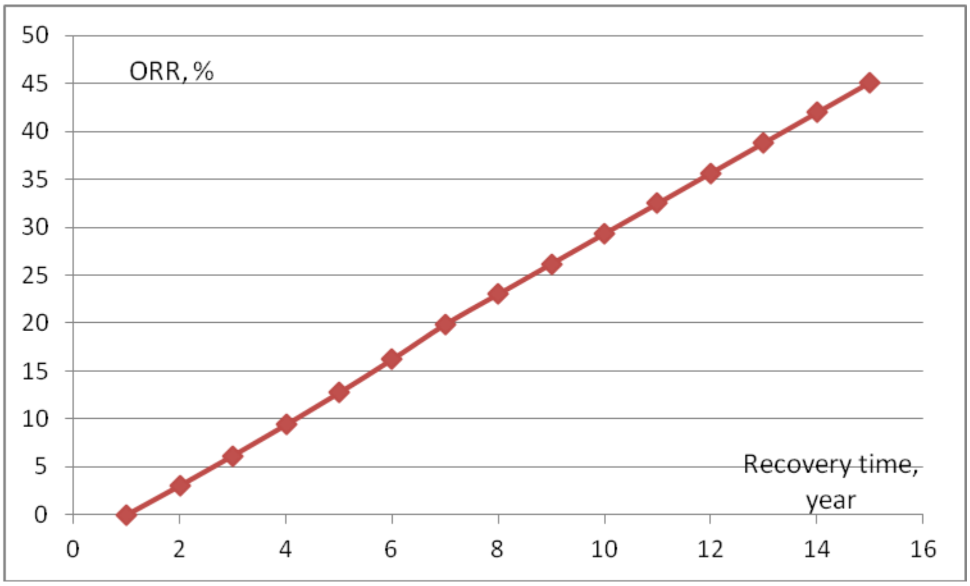

Fig. 20. ORR vs. recovery time

Compare these two variants of the location of the contours, we conclude that the flooding with the location of injection wells at the perimeter of the reservoir would lead to better results (at recovery time - 17 years, ORR - 53%) than the other options.

2.5. Gas injection

Of particular interest is the Vikulovskya structure in terms of gas injection from the University structure, which is located 40 km northeast of Vikulovskoy at a depth of 70 meters.

Oil production on the plateau of the University is 12500000 m^3 per year (xx bbl/day). There are two fundamentally different solutions with respect to the associated gas injection from the University to Vikulovskya:

1) The injection of gas produced from the University at the Vikulovskoy

2) The transportation of all products to the Novaya Zemlya

We will look at these options.

A. Injection of gas produced from University at Vikulovskoy (Fig.21)

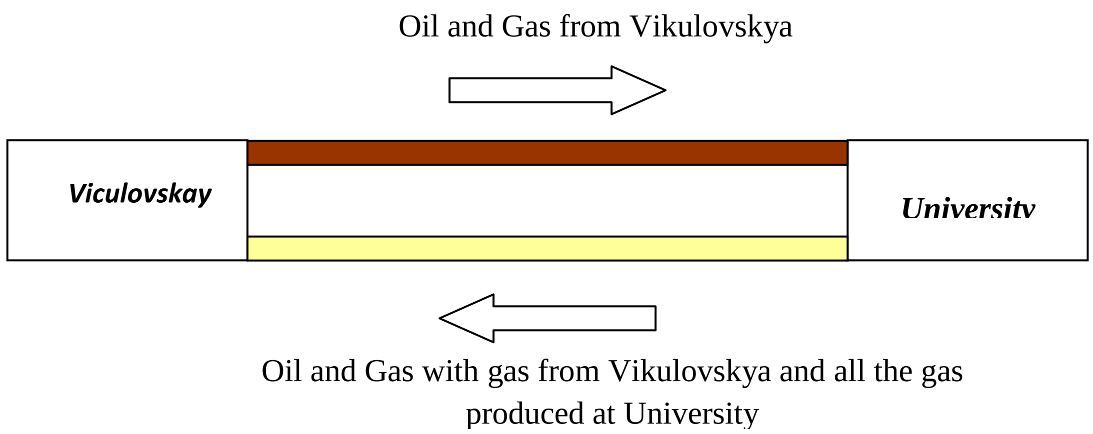

Fig. 21. Schematic diagram of the hydrocarbon transport in the first option

Use the equation of material balance for the maintenance of reservoir pressure (eq. 7):

$$
\begin{aligned}
&(QR_s + G)B_g = QB_o \\
&Q - oil\ recovery\ from Viculovskaya \\
&G - gas\ recovery\ from University \\
&R_s - gas\ saturation \\
&B_o - oil\ volume\ factor \\
&B_g - gas\ volume\ factor
\end{aligned}
\tag{7}
$$

Solving it with respect to Q, we have (eq.8):

$$Q = \frac{B_g R_s}{B_o - R_s B_g} Q_{univer} \tag{8}$$

From this $Q=1,67Q_{univer}$

With the help of Dyupii (eq.2) we define the maximum possible flow rate for a pressure difference of 15 MPa; q = 1840 m^3/day. 32 wells should be drilled to produce oil. 16 wells are required for gas injection. This variant also requires an additional platform at the University for compressor installing.

At 25 years of operation of the recovery rate is 35%.

2. The transportation of all products to the Novaya Zemlya, Figure 22

Use the equation of material balance for the maintenance of reservoir pressure (eq. 9):

$$QB_o = Q_{univer} R_s B_g \tag{9}$$

From this $Q=0,625Q_{univer}$

With the help of Dyupii (eq.2) we define the maximum possible flow rate for a pressure difference of 15 MPa; q = 1840 m^3/day. 12 wells should be drilled to produce oil. 6 wells are required for gas injection. All products (oil and gas from Viculovskay and oil from University) go to Novaya Zemlya.

The design of the platform on the University structure is greatly simplified. There is a need to use a tunnel solution to transport products to the Novaya Zemlya.

At 25 years of operation the recovery rate is 13%.

At 35 years of operation the recovery rate is 18%.

For an Analysis of development options, see Chapter 2.6

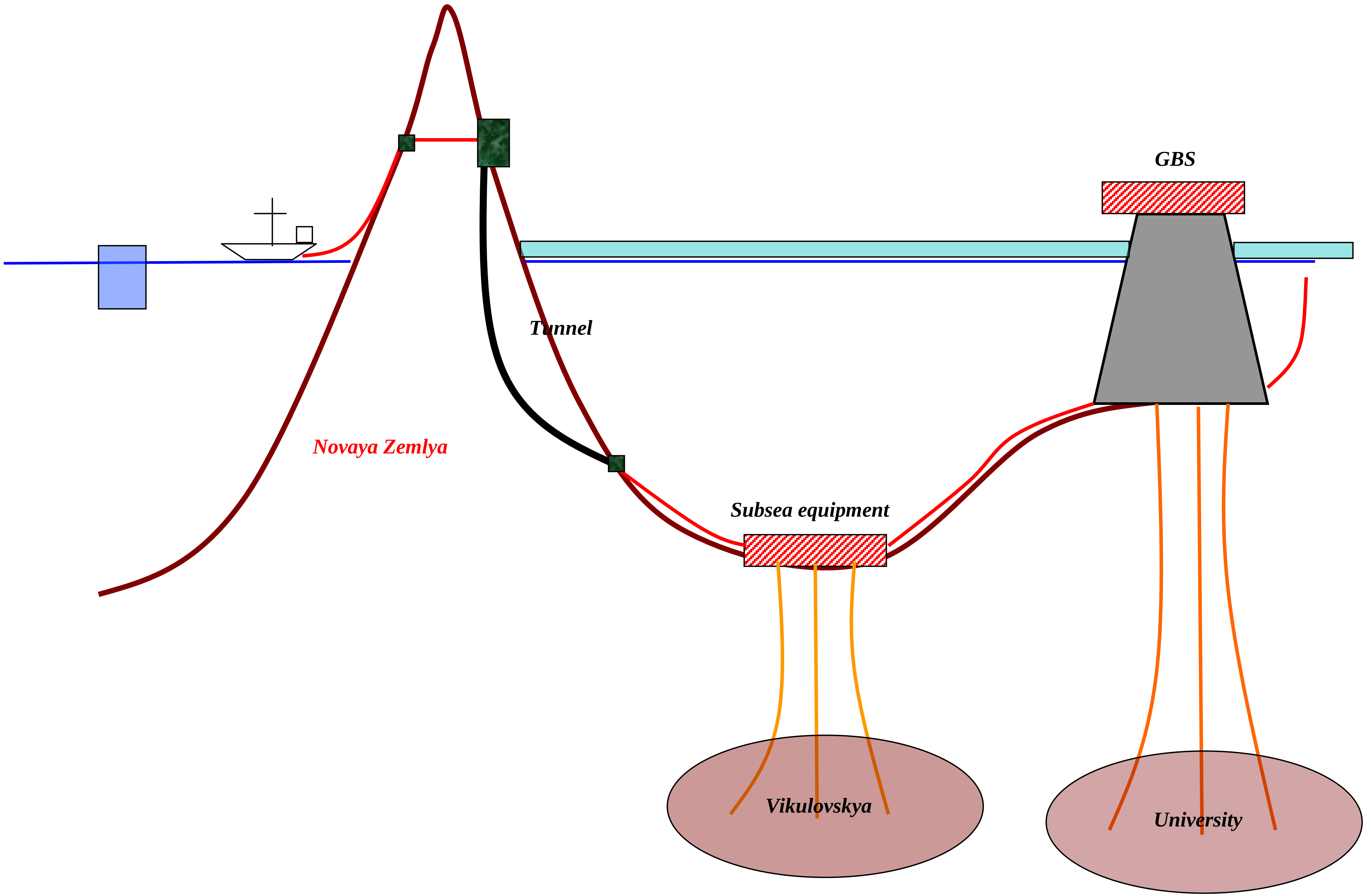

Fig. 22. “Tunnel” concept for Kara Sea development with production and compression equipment located at the lower end of the tunnel.[4]

2.6. Analysis of the development options

After analyzing the three possible options for the development of the Vikulovskaya structure, the following summary table has been obtained (Table 16):

Table 16.Development options for the Vikulovskaya structure.

Drive/mode	Recovery time, year	ORR, %	Maximum production rate, m^3/day	Number of wells
Depletion	**40**	**11**	**20000**	**30 producers**
Water flooding	**17**	**53**	**100000**	**20 injectors 20 producers**
Gas injection 1	**25**	**35**	**60000**	**16 injectors 32 producers**
Gas injection 2	**25 (35)**	**13 (18)**	**22000**	**6 injectors 12 producers**

Discussion of development options

- *Depletion drive:*

Advantages:

- an average number of wells (30)

- a relatively low level of oil production allows the development of the Vikulovskuyu structure as a satellite of the University through underwater pipeline and umbilicals

- do not need any additional equipment at the University for injection into the formation of any agents.

Disadvantages:

-long term development,

- low recovery factor,

- the problem of gas transport from the University and Vikulovskaya structures is not solved.

- *Water flooding*

Advantages:

-very high ORR (53%)

-short-term development.

Disadvantages:

- need an additional high-pressure discharge line,

- very high level of production makes transportation of oil capital-intensive,

-. the problem of gas transport from the University and Vikulovskaya structures is not solved

- *The maintenance of reservoir pressure by gas injection from the University and Vikulovskoy structure.*

*A*dvantages:

- A high ORR (35%),

- The problem of transport of gas from the Vikulovskaya and University structures is solved by traditional methods

Disadvantages:

- very large number of wells (48)

- need a high pressure gas pipeline at a distance of 60 km,

- need an additional compressor unit (most likely on a separate platform)

- a large number of subsea pipelines.

- *The maintenance of reservoir pressure by gas injection from the University structure and the subsequent transport of production to the Novaya Zemlya*

Advantages:

- small number of wells (18)

- Solved the problem of gas transportation from the Vikulovskaya and University structures by non-traditional methods

- - a relatively low level of oil production allows develop Vikulovskuyu structure as a satellite of the University through the underwater pipeline

- an application of the "tunnel" concept allows to achieve high flexibility of the project

Disadvantages:

- in case recovery time is 25 years, ORR is only 13%

- need a high pressure gas pipeline at a distance 60 km,

- need an additional compressor unit,

- untested solution for transport of gas.

Chapter 3. Components of the subsea system.

There are two types of field development with subsea completions - using templates or using a cluster solution (Christmas trees are separated with a central manifold) [9].

In my opinion, for the development of Vikulovskoy where a large number of wells is required. A large number of templates can lead to instability in the clay, which form a bottom and a fewer number of templates should be chosen.

The main elements of a subsea production systems are:

3.1 Wellhead systems (Fig.23)

Drilling a subsea well from a floating drilling rig or completing a well subsea requires a subsea wellhead. Subsea wellheads serve several purposes:

- to support the subsea blowout preventer (BOP) and seal the well casing during drilling

- to support and seal the subsea production tree

- to support and seal the well casing.

-to support and seal the production tubing hanger.

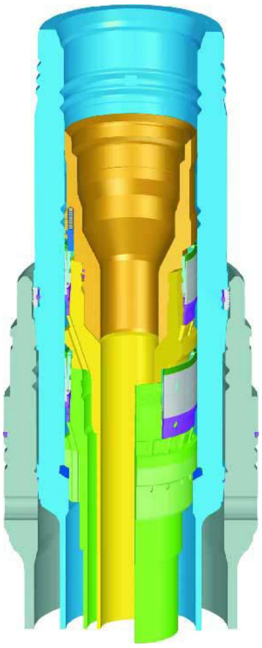

Fig. 23. Wellhead systems [15]

3.2. Subsea Christmas (Xmass) tree [15]

The subsea tree is basically a stack of valves installed on a subsea wellhead to provide a controllable interface between the well and the production facilities. Some specific functions of a subsea Christmas tree include the following:

- Sealing the wellhead from the environment by means of the tree connector.

- Sealing the production bore and annulus from the environment.

- Providing a controlled flow path from the production tubing, through the tree to the production flow line. Well flow control can be provided by means of tree valves and/or a tree-mounted choke.

- Providing access to the well bore via tree caps and/or swab valves.

- Providing access to the annulus for well control, pressure monitoring, gas lift, etc.

- Providing a hydraulic interface for the down hole safety valve.

- Providing an electrical interface for down hole instrumentation, electric submersible pumps, etc.

- Providing structural support for flow line and control umbilical interface.

There are two types of subsea Xmass trees – vertical (Figure 24) and horizontal (Figure 25) [9]

Vertical Xmass tree (Fig 24):

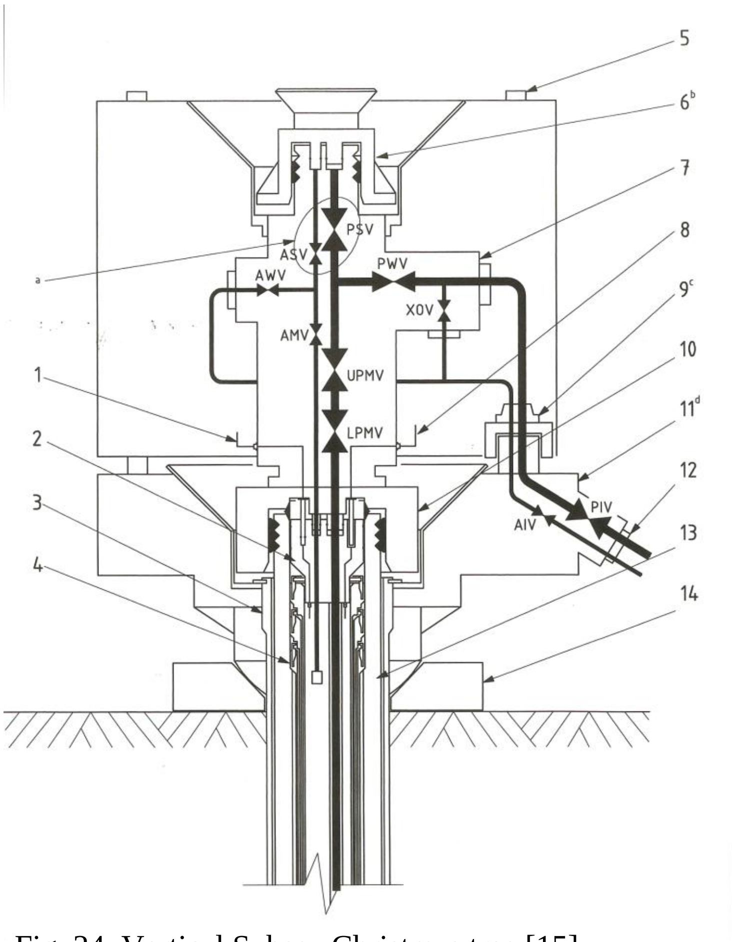

Fig. 24. Vertical Subsea Christmas tree [15]

Key

1 SCSSV control line
2 tubing hanger (TH)
3 conductor housing
4 casing hangers and seal assemblies
5 guideposts (optional)
6 XT cap
7 Xmas tree (XT)
8 DHPTT monitoring line
9 flowline connector
10 XT connector
11 guidebase
12 flowline/tie-in spool connector
13 wellhead
14 drilling guidebase or template slot

a PSV and ASV may be substituted with plugs.
b XT cap may be pressure-containing or non-pressure-containing.
c Flowline connection shown connected to Production guidebase, but may also be connected directly to XT.
d Production guidebase shown (allows connection of flowlines).

Horizontal Xmass tree (Fig.25)

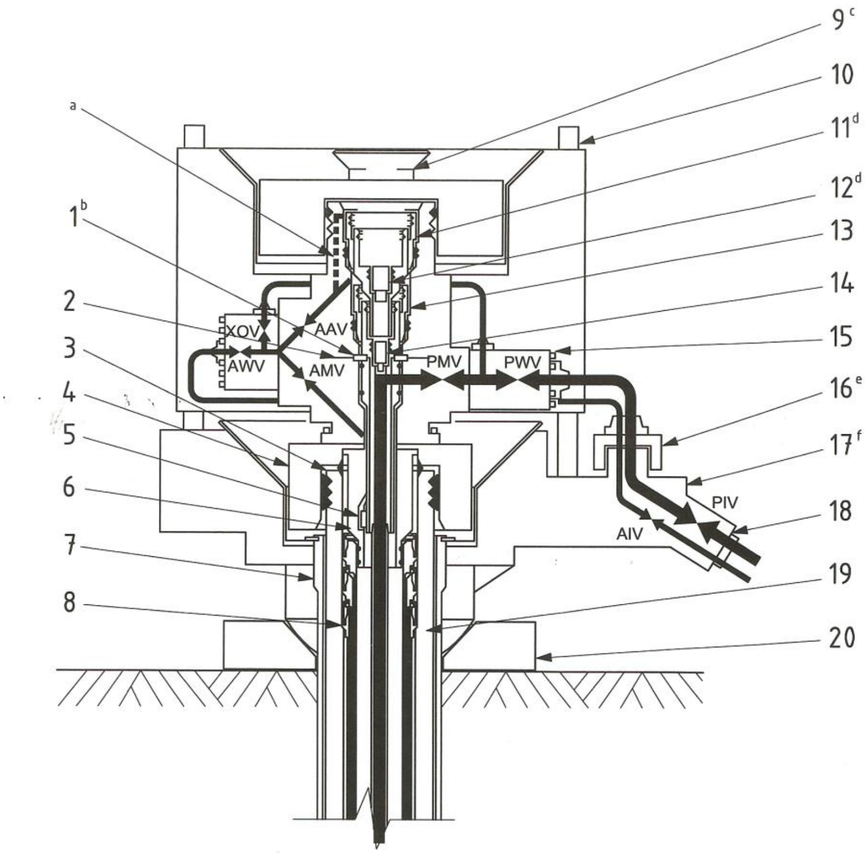

Fig. 25. Horizontal Subsea Christmas tree [15]

Key

1 horizontal stroking couplers/connectors
2 SCSSV and DHPTT lines
3 wellhead
4 XT connector
5 TH orientation helix
6 completion stab sleeve
7 conductor housing
8 casing hangers and seal assemblies
9 XT cap
10 guideposts (optional)
11 internal tree cap (ITC)
12 ITC plug
13 tubing hanger (TH)
14 TH plug
15 Xmas tree (XT)
16 flowline connector
17 guidebase
18 flowline/tie-in spool connector
19 wellhead
20 drilling guidebase or template slot

[a] Permits annulus access without having to remove ITC.
[b] Hydraulic/CL lines may be made up with static seal mechanisms.
[c] XT cap may be pressure-containing or non-pressure-containing.
[d] ITC shown with plug. ITC may also be blind or fitted with ball valve.
[e] Flowline connection shown connected to Production guidebase, but may also be connected directly to XT.
[f] Production guidebase shown (allows connection of flowlines).

At the Vikulovskoy structure it is more convenient to use the horizontal Christmas tree, because during the very short season of open water, one can break the installation process into two stages.

3.3 Manifold (Fig.26)

The general function of a subsea manifold is to gather and distribute production through an arrangement of piping and valves. Some specific functions are:

- to collect the flow from several field production gathering flowlines and deliver that flow to a larger production export pipeline.

- to segregate high pressure and low pressure production from individual wells and deliver it to a well test header or a well test flowline.

- to isolate the production from individual wells and deliver it to a well test header or a well test flowline.

- to control the flow from individual wells by means of subsea chokes. Wells may be choked at the trees or at the manifold.

- to distribute injection water or gas from a common supply header to individual injection wells (water injection or gas injection manifolds).

- to distribute lifted gas from a common lift gas header to individual wells (lift gas manifold).

- to facilitate pigging of subsea pipelines by provision of pig isolation valves, tees and pig detector instrumentation mounted on the manifold structure.

- to provide structural support of the piping and flowline connector at the flowline connection interface.

Fig. 26. Manifold [15]

3.4. Templates (Fig.27)

The primary function of a subsea template is to provide guidance for positioning wells and controlling their positions relative to one another. In addition, a subsea template may incorporate many of the functions of a subsea manifold described above, all in one integral assembly. Some specific functions of a subsea template are:

- to provide a guide for positioning the well conductor and guiding the conductor during installation.

- to control spacing between adjacent well conductors.

- to provide guidance and support for the BOP in some cases.

- to provide guidance and support for well completion equipment (e.g. trees) in some cases.

- to accommodate pre-installation of well flowline piping and facilitate interface of the production trees with their flowlines.

- to accommodate pre-installation of tree control hardware and facilitate interface of the production trees with their controls.

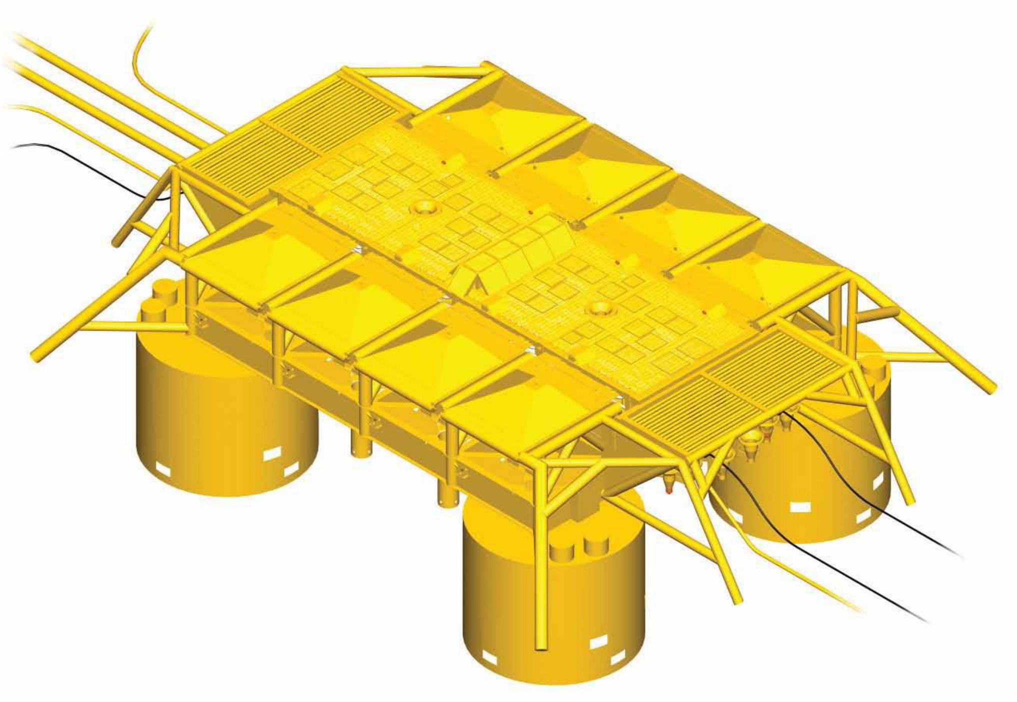

Fig. 27. Template [15]

Chapter 4. Subsea module installation in the southern part of the Kara Sea.

There is a number of limiting factors enhancing the application of subsea technologies, such as long distances to the shore, ice gouge of the seabed at the location of the templates or pipelines, limited service and maintenance availability in ice infested waters and an limited installation period.

Installation is one of the crucial marine operations related to the subsea technologies, which can be executed during ice-free period lasting in some areas about 3-4 month. Therefore correct weather forecast; forecast of wave conditions, assessment and determination of available favorable installation period is a key issue.

We will show the limitations of subsea installation related to wind and waves [1]. Optimal time period for installation, probability of success per one season and mean time of installation have been determined on the basis of accumulated in RMRS' directories statistics for a relevant area, the Norwegian Sea [16].

This work is of practical interest and can be extended to the wide range of marine operations, such as transportation, installation, repair and maintenance operations.

Average time of subsea modules installation (including operations to prepare a lift) is on the basis of world experience assumed to be 48 hours. It is also assumed that installation operation is limited due to safety reasons by a wave height equal to 2m. Therefore, we will here consider a project where execution of installation operation requires «weather window» of 48 hours with wave height <2m.

The mean duration of the «weather window» (wave height is less than 2m) and the number of these windows for one month can be estimated by using statistics from RMRS (Russian Maritime Register of Shipping). Experience [5] shows that an exponential distribution describes the duration, D, for a given event reasonably well (eq.11).

$$P(D > d \mid H < h) = \exp\left(-\frac{d}{D}\right) \qquad (11)$$

where D – mean duration of «weather window» (hours), d – time required for installation (hours), H – maximal wave height within 48 hours, h – limiting wave height, P – probability of success for one attempt.

Estimates for the Vikulovskaya perspective oil and gas field in the Kara Sea have been considered. The following information has been obtained (Table 17; Figures.28-30):

1) Probability of successful installation in one attempt

2) Probability of successful installation (occurrence of «weather window») for one month

3) Probability of successful installation for one season (for ice-infested waters)

4) Mean time required for subsea installation for each month.

5) Wave period corresponding to the maximal energy (this characteristic is important for the choice of means involved in installation process).

Table 17. Probability of completing installation work

Month	*Probability of not-completed operation in one attempt*	*Probability of not-completed operation during one month*	*Probability of not-completed operation during one season*
July	0,464	0,006	4,45E-07
August	0,536	0,012	7,21E-05
September	0,736	0,068	0,006
October	0,612	0,081	0,081

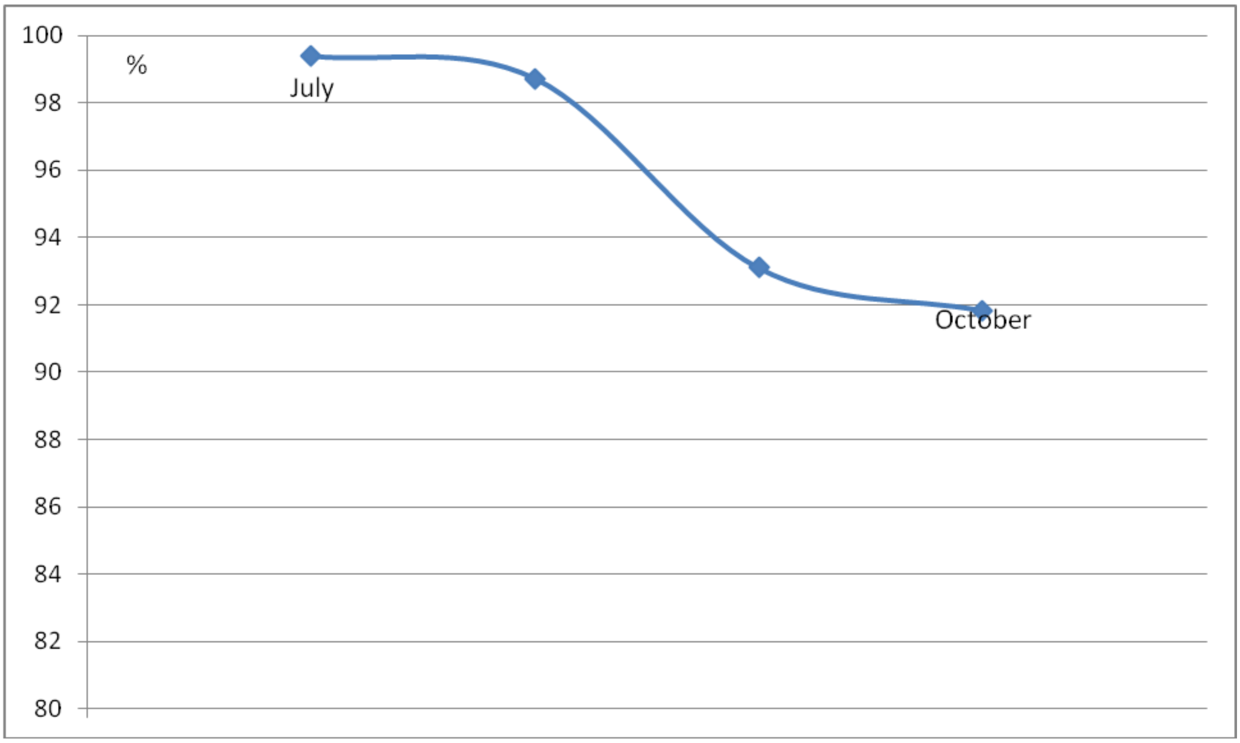

Fig. 28. Probability of successful installation for each month (the Kara Sea)

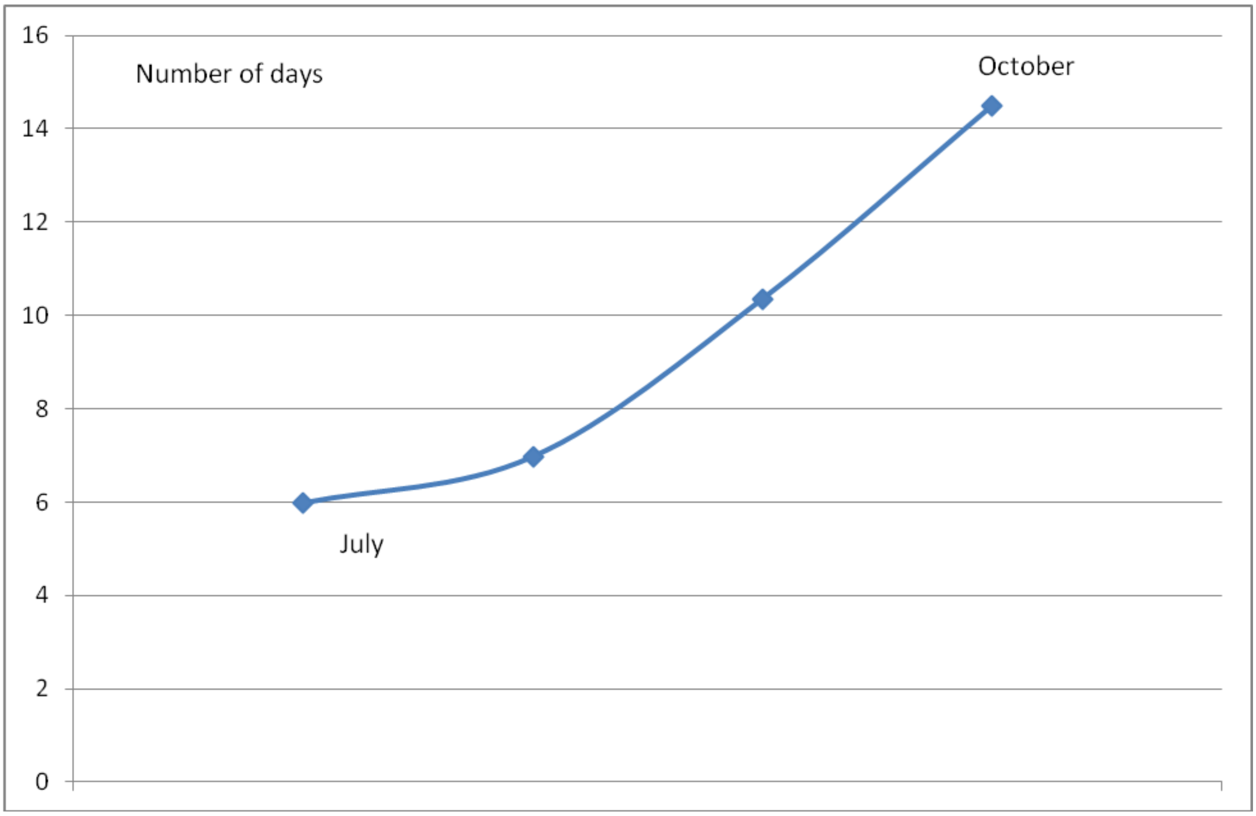

Fig. 29. Mean time required for installation (the Kara Sea)

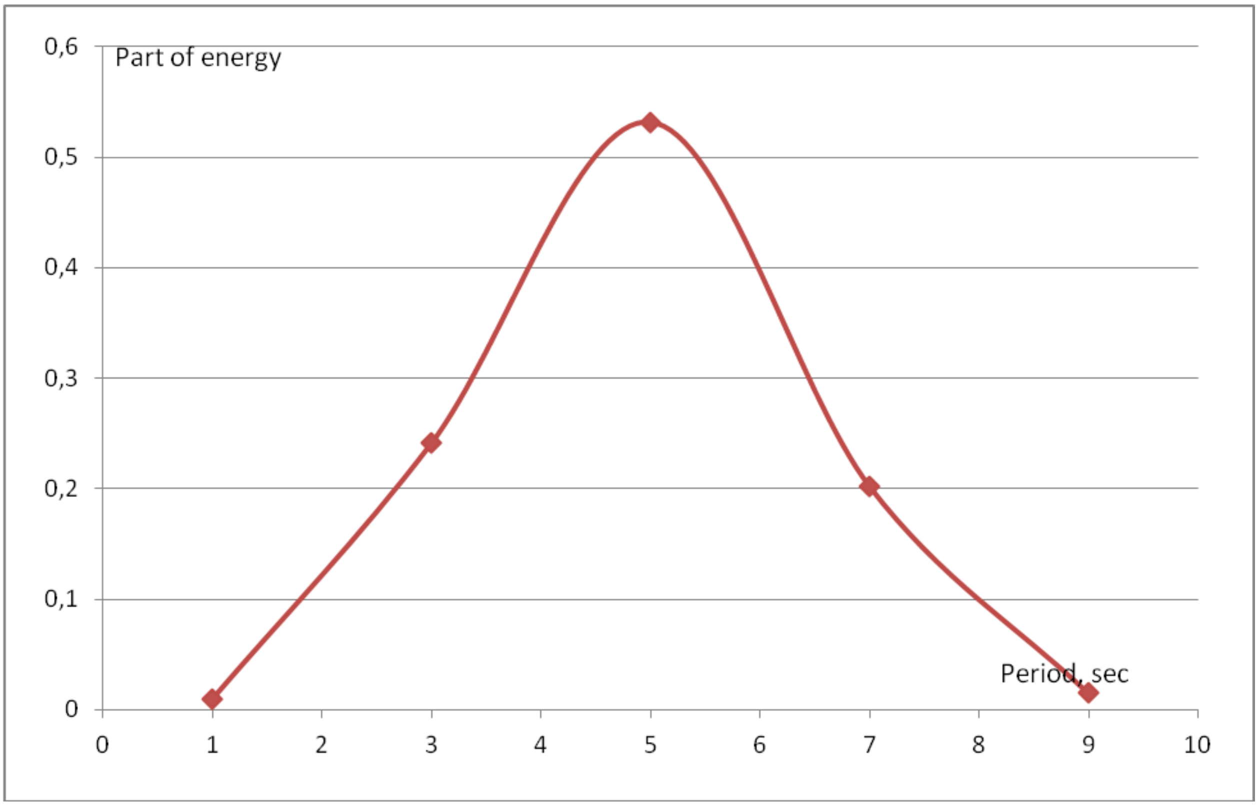

Fig. 30. Energy vs. period of wave (the Kara Sea)

Analysis of results obtained for subsea installation work in the Kara Sea shows that:

1) The period of time available for subsea installation (the ice-free period) is limited by 4 months in the year due to the sea ice.

2) The probability of successful installation is higher than 90% for each month of the ice-free period, decreasing from 99% in July to 92% in October. The most favorable time for installation is July and August.

3) Risk of not-completed installation in one season is equal to 8% if installation starts in October and 0,5% if installation starts in September. It means that the installation process will be successful with the probability of 99%, if it starts on September 10th or earlier.

4) The mean time required for subsea installation varies from 6 days in July to 14 days in October. It should be noted, that the vessel's cost is proportional to this time (not including mobilization /demobilization).

5) Wave energy distribution vs. period (spectrum) in the Kara Sea is similar to wave energy distribution in the North Sea (reaching its maximum at 5 seconds period). It means that fleet (barges) successfully used in North See, can also be used in Kara Sea (from the point of the wave climate).

Conclusions.

The main conclusions are:

- to use subsea production systems is possible, and in some parts of the Kara Sea it is the only way to provide cost-effective developments of hydrocarbon deposits.

- the main problem, whose solution is the key to the successful application of underwater technology, is the challenges of year-round drilling and the lack of access to equipment for nine months. Without answers for these questions, the use of subsea developments in the Kara Sea is highly unlikely.

- for development of the so called University structure, which is targeted at the first stage of development of the Kara Sea, one has to note the issues of utilization of associated gas, export of which and other methods can be difficult. Injection of gas into the Vikulovskaya structure will maintain the pressure in the structure and significantly improve recovery.

- the application of tunnel concepts as proposed in [4] can be effective in the development of hydrocarbon fields located at the East-Prinovozemelskoy trench

- Wave energy distribution vs. period (the wave spectrum) in the Kara Sea is similar to the distribution of waves in the North Sea (reaching its maximum at 5 seconds period). It means that fleet (barges) successfully used in North See, also can be used in Kara Sea.

- an equipment installation process will be successful with the probability of 99%, if it starts on September 10th or earlier.

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