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MASTER'S THESIS

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Writer: Roman Shulkin	…………………………………………… (Writer's signature)
Faculty supervisor: **Ove Tobias Gudmestad** External supervisor(s): **Anatoly Borisovich Zolotukhin**	
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Abstract

This Master's thesis describes the concept development of a stimulation and well service vessel and the evaluation of its operational limits in Northern Caspian Sea conditions during a whole year of operation (all 4 seasons). Possible options and solutions are discussed on the basis of the analysis of world experience and existing technologies for similar conditions.

An integrated approach for solving this problem includes three parts:

- The selection of the optimum vessel, that can be specially constructed or upgraded to carry all the equipment, that is needed to ensure the successful down-hole treatments in challenging marine and ice conditions.
- The selection of the optimum deck equipment layout, which will satisfy the necessary parameters, such as vessel stability and efficiency for the chosen down-hole operations technology.
- Operational limits discussion and risk evaluation. Suggestion of effective mitigation measures.

To solve this problem analysis of up-to-date technologies and several types of calculations were provided, relevant geographical, environmental and reservoir data was examined. The most attention was paid to vessel selection, vessel modelling and stability calculations, ice resistance evaluation. Modelling of a vessel was performed in the "Free!Ship" software, ice resistance calculations are based on actual theoretical models. The obtained results were discussed and it was proven, that the chosen vessel is stable and can carry all the equipment, as well as that it can be used during harsh winter conditions.

All calculations, analysis and proposed solutions were made in accordance with local rules and regulations.

In conclusion, recommendations wrap up the thesis and summarize the whole research and key findings.

The thesis was carried out in conditions of the limited initial data. The obtained results can be used for further concept development.

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Introduction

The Caspian region is rich in natural resources, which are represented by mineral, biological, agro-climatic, balneological and recreational components. Among the mineral resources, the special role belongs to the huge reserves of hydrocarbons – oil, gas and gas condensate.

First oil production began in the late XIX century on the shores of the Caspian. Then in the mid XX century, the Caspian shelf began to develop. At the end of XX - beginning of XXI century Caspian oil is experiencing a second birth. According to the prediction results there are 15-22 billion tons of oil and 12-18 trillion m^3 of gas. Large fields such as Korchagin (Russia), Filanovsky (Russia), Kashagan (Kazakhstan), Shah Deniz (Azerbaijan), Hvalynskoe (Russia) were discovered on the Caspian shelf.

Environmental conditions such as currents, waves, icing and unstable hydrological regime are considered as the most important factors affecting offshore field development and ice-resistant facilities design. Nevertheless, the operational skills in such conditions are still under development. Thus, modern oil and gas industry requires up-to-date technology and techniques. Each particular field is unique and should have an individual development approach.

The most complete extraction of oil, gas and condensate is the main direction of rational use of mineral resources. Therefore, it is very important to use modern technologies of well service, stimulation of production and enhanced oil recovery methods. For offshore fields this problem is of outstanding importance.

One of the main objectives of this paper is to select the most suitable stimulation and well service vessel and deck equipment layout for shallow waters of the Northern Caspian Sea and Filanovsky cluster of fields based on the world experience, environmental conditions and personal knowledge. This part includes operational limits analysis, ice resistance calculations for a vessel and stability modelling in “Free!Ship” software.

Field development is always connected with the human intervention into the environment thus, it is necessary to follow all governmental regulations, which are also considered in this thesis. Consequently, second objective is to evaluate the risk and propose sufficient mitigation measures.

Thesis organization

Chapter 1 (Geography and petroleum resources of the Caspian Sea) is an overview chapter. It includes information about geographical position; parameters such as area, depth and water volumes; petroleum resources potential and importance of the Caspian Sea.

Chapter 2 (Environmental conditions of the Northern Caspian Sea) contains climate of the sea, its hydrologic characteristics, wave, currents, winds and ice conditions. It allows getting the most complete understanding of all environmental conditions, features and problems, which they can cause.

Chapter 3 (Scope of use) defines the urgency of the problem and potential scope of use. In this chapter, the Filanovsky cluster of fields is observed and proposed as the best and most likely field of application.

Chapter 4 (Main objects of the Filanovsky cluster of fields infrastructure) describes the existing and future infrastructure and field development layout. This chapter includes information about types of used platforms, transport systems and their location.

Chapter 5 (Technology concept for a vessel for hydraulic fracturing) covers an integrated approach for hydraulic fracturing and well interventions for offshore oil and gas fields, which includes two main parts: selection of the optimum vessel; optimum down-hole technology and necessary equipment. Main advantages, difficulties and operational limits are discussed in the chapter.

Chapter 6 (World experience). This chapter is about already conducted offshore operations in the world and introduces the potential of offshore down-hole treatments. Four projects were considered: Russia (Northern Caspian Sea), UAE (Offshore Abu Dhabi), India (Krishna Godavari Basin) and two specially built stimulation vessels (Baker Hughes Blue Dolphin and Blue Orca).

Chapter 7 (Optimum vessel selection and analysis) describes limiting criteria and drivers for optimum vessel selection. Limitations were classified into first and second order. Six types of vessels were compared by the variety of parameters and the most suitable was selected.

Chapter 8 (Ship motions) gives the relevant theory for vessel motions analysis.

Chapter 9 (Stability) includes general terms and theory for initial stability analysis. Special requirements of DNV and Russian Maritime Register of Shipping were considered and used in analysis. Model of the ship hull was made in the "Free!Ship" Software and simulation was conducted. It is based on the default tug model and changed to suit the Arcticaborg parameters. Hydrostatics calculations were provided and cross curves of stability were obtained for further analysis.

Chapter 10 (Sea ice aspects) introduces the basic theory about ice actions and mechanics. Main terms related to the ice physical and mechanical properties are revealed. Values for each parameter of the Caspian Sea ice obtained from the field studies are presented. On their basis, ice resistance calculations for different ice thickness conditions were made and obtained results were discussed.

Chapter 11 (Optimum equipment selection and deck equipment layout) tells about types of proposed fracturing and other stimulation equipment. Limitations during design stage and recommended equipment layout on the deck.

Chapter 12 (Health, safety and environment regulations (HSE)) contains definition of the structure of Russian normative base in the field of oil and gas industrial safety. Three types of Federal norms and rules for the HSE approved by Rostekhnadzor are considered and main terms are discussed in detail.

Chapter 13 (Risk analysis) describes general risk classification and all risks, that can happen during operations execution. Risk analysis is obtained by two methods: risk matrix and bow-tie analysis. Mitigation measures are proposed in the chapter.

Finally, conclusions and recommendations wrap up the thesis and summarize the whole research and key findings.

Chapter 1. Geography and petroleum resources of the Caspian Sea

The Caspian Sea is a unique natural reservoir of our planet that lies between Azerbaijan, Iran, Kazakhstan, Russia and Turkmenistan with the surface area of 379000 km^2, a drainage area of a 3.5 million km^2 and volume of 78000 km^3 (see **Figure 1.1**). Geographical coordinates of extreme points of the modern Caspian water area: in the north — 47°07' N, in the south - 36°33' N, in the west - 46°43' E and in the east — 54°03' E [21].

Figure 1.1 – Map of the Caspian Sea.

Source: [66].

The Caspian Sea is complicated reservoir with specific features. Level of the sea fluctuates about 27-28 meters below global ocean level. According to the bathymetric features and morphological characters, the Caspian Sea conventionally separated into northern, central and southern basins. The average morphometric data corresponding to the modern sea level is provided in **Table 1.1** [31].

Table 1.1 – Morphometry of the Caspian Sea.

Part	**Square, 10^3 km^2**	**Volume of water, km^3**	**Maximal depth, m**
Northern	104,6	0,49	11
Central	138,2	26,75	788
Southern	149,8	51,40	1025
All sea	392,6	78,64	1025

The Caspian Sea region is one of the oldest oil-producing areas in the world and is one of the most important sources of global energy production. The area has significant amounts of oil and natural gas from both onshore and offshore fields. **Figure 1.2** shows main countries-producers and the total potential of the Caspian Sea.

U.S. Energy Information and Administration (EIA) estimates that there were 7.6 billion m^3 of oil and 8.3 trillion m^3 (tcm) of natural gas in proved and probable reserves within the basins that make up the Caspian Sea and surrounding area in 2012. Offshore fields account for 41% of total Caspian crude oil and lease condensate (3.1 billion m^3) and 36% of natural gas (3 tcm). In general, most of the offshore oil reserves are in the northern part of the Caspian Sea, while most of the offshore natural gas reserves are in the southern part of the Caspian Sea. EIA estimates another 3.2 billion m^3 of oil and 6.9 tcm of natural gas in as yet undiscovered, technically recoverable resources. Much of this is located in the South Caspian Basin, where territorial disputes over offshore waters hinder exploration. According to EIA, the Caspian Sea region produced an average of 0,4 million m^3 per day of crude oil and lease condensate in 2012, around 3.4% of the total world supply [56].

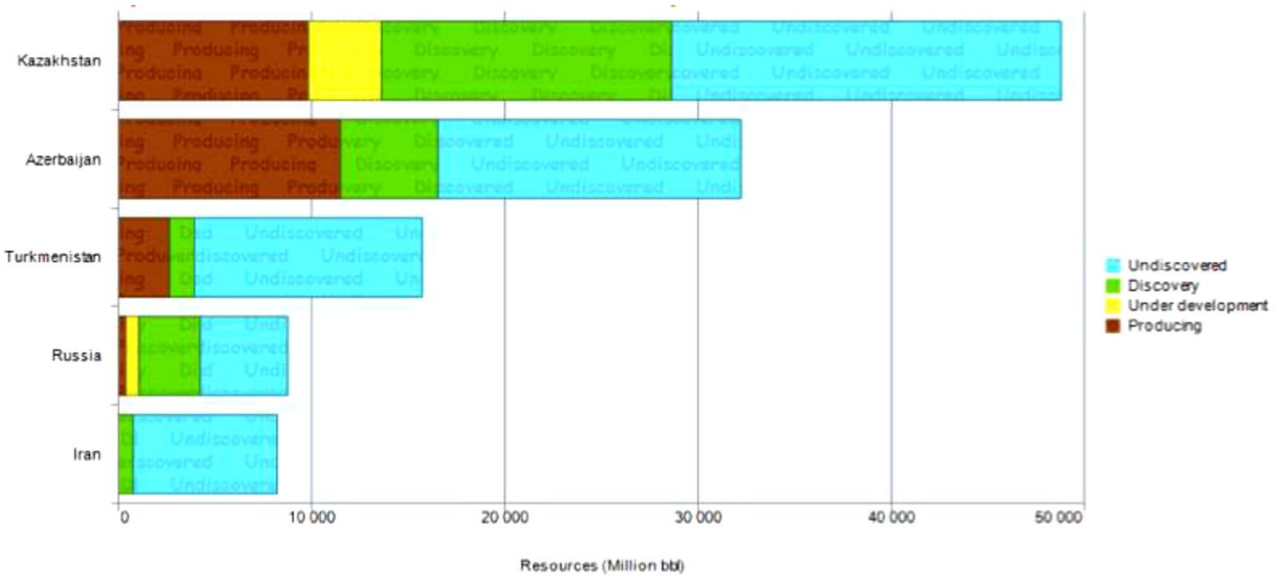

Figure 1.2 – Potential of the Caspian Sea.

Source: [45].

Chapter 2. Environmental conditions of the Northern Caspian Sea

2.1. Main parameters

The typical environment conditions of the Northern Caspian Sea, which are used in further calculations, are given in the **Table 2.1** [3].

Table 2.1 – Main parameters of the Northern Caspian Sea.

Parameter	The North Caspian Sea conditions
Latitude	47 °N
Max. wind gust, m/s	40
Average wind velocity, m/s	6
Min. air temp., °C	-38
Average annual water temperature, °C	11-13
Salinity, ppt	6-11
Sign. wave height, m	5
Max. current velocity, m/s	1.29
Average current velocity, m/s	0.6 (at the sea level)
Freezing up (average)	Middle of November – North East part
Clearing (average)	April
Average open water, days	225
Multi-year ice, %	-
Max. level ice thickness, m	0.9
Rafted ice thickness, m	1.8 (twice level ice thickness)
First-year ridge thickness, m	from 1.2 up to 12
Multi-year ridge thickness, m	-

2.2. Climate

The water area belongs to a zone of continental climate, relatively low air humidity, low rainfall and big air temperature drops.

The climate is characterized by the cold winter and the warm summer. In the winter, unstable weather with violent oscillations of air temperature prevails. High possibility of wind direction changes, which sometimes turns into storm. In the spring, unstable weather with strong storm activities prevails.

Summer is steady hot; preferentially dry with light breezes and a good visibility. In an early autumn, the dry clear weather remains. At the end of fall, the weather sharply turns into cold and cloudy. Violent oscillations of air temperature and often rains are obtained.

Annual average temperature of the water area is 10 °C.

The coldest months are January and February. The warmest period is July – August. An annual average absolute air humidity is 9,3 g/m3, relative air humidity is about 82%. Air humidity on the water area is quite high. The smallest value of relative air humidity is observed in June-July, maximum is during the winter period.

During the autumn and winter periods, southeast winds prevail. In the summer, northern directions occur.

Within a year, precipitations are distributed quite uniformly. The minimum value of precipitates is in February-March (up to 10 mm), the most is in June-July (up to 23 mm). Precipitates are generally in the rain form. Snow cover on a surface is distributed extremely unevenly.

The annual amount of days with fog are 123, 108 days from them are during the winter period from November to March. Usually, fogs are observed at morning hours or during the light breeze.

2.3. Hydrologic characteristics

Long-term average annual water temperature of 11.2 °C fluctuates in a surface layers from a maximum of 27.9 °C (July) to a minimum -0.09 °C (January). In the cold season (November-March), equilibrium of temperatures is observed.

Salinity of water in the projected zone in some ways depends on volume change of the Volga river flow and the water exchange with the central part of the Caspian Sea. The average annual salinity is equal to 9.46 ‰ (see **Figure 2.1**). During the winter period, salinity of seawater increases due to formation of ice and weak Volga waters inflow [40].

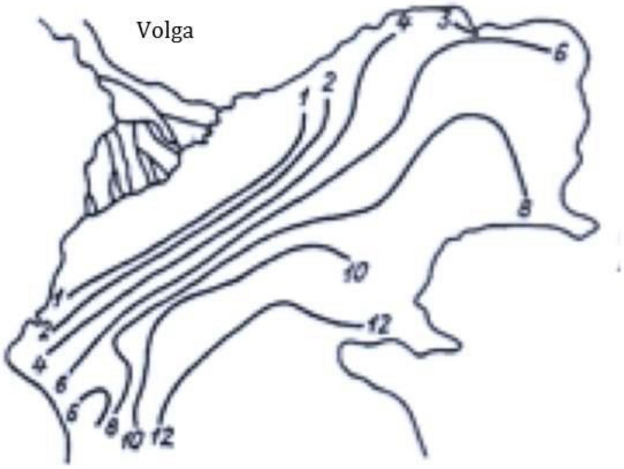

Figure 2.1 – Salinity distribution (ppm) in April for the period 1940-1963.

Source: [40].

Currents play an important role in hydrodynamic mode of the Northern Caspian Sea. In addition, wind currents have a major importance (see **Figure 2.2**).

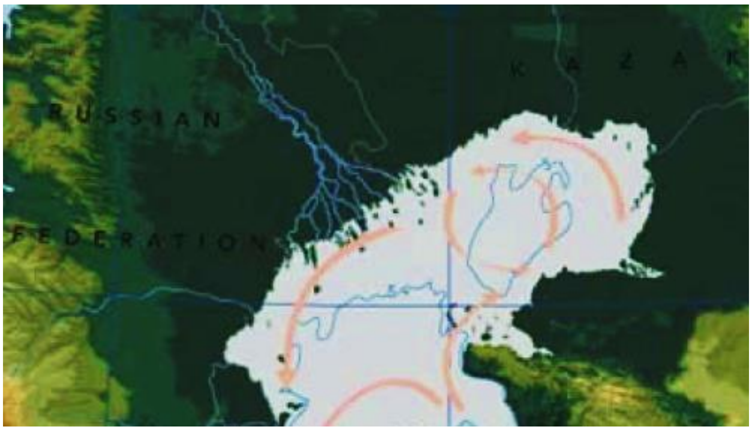

Figure 2.2 – Main currents of the Caspian Sea

Source: European Environment Agency, 2005.

Winds with a speed less than 5 m/s do not cause considerable and steady currents. At unstable and light breezes, the directions of currents change insignificantly and can vary a lot, as far as the largest role is played by gradient and inertial (residual) currents. **Figure 2.3** shows the probabilities of different with speeds at the Northern part of the Caspian Sea.

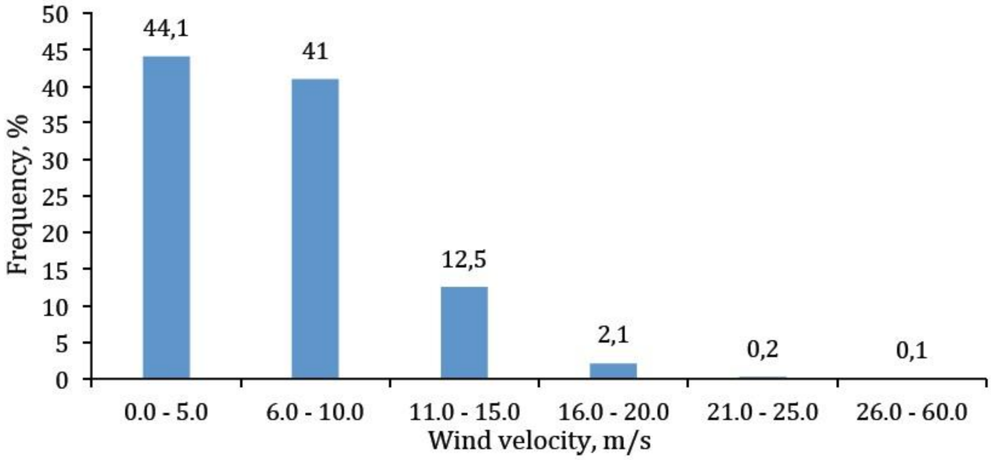

Figure 2.3 – Frequency of the wind speed for the period 1888-2006.

Source: http://www.esimo.ru/atlas/Kasp.

The wind-induced, steady current (70% of overall time), is formed by the steady wind with a speed more than 5 m/s. The general pattern of currents has gyre circulation. The maximum speed of a wind current on a surface for the storm period with possibility of 1 time in 100 years is 1.29 m/s.

Typically, steady currents occur during east, southeast, and also northwest and western winds.

From December to March, when the Northern Caspian Sea is usually covered with ice, subglacial currents are extremely weak. In a superficial layer, current speed is 36 – 85 cm/s, and the average value is 60 cm/s.

Sea depth in the water area increases from the North to the South. The Filanovsky field is located in the more shallow northern part with sea depth of 4-10 m (see **Figure 2.4**) [42].

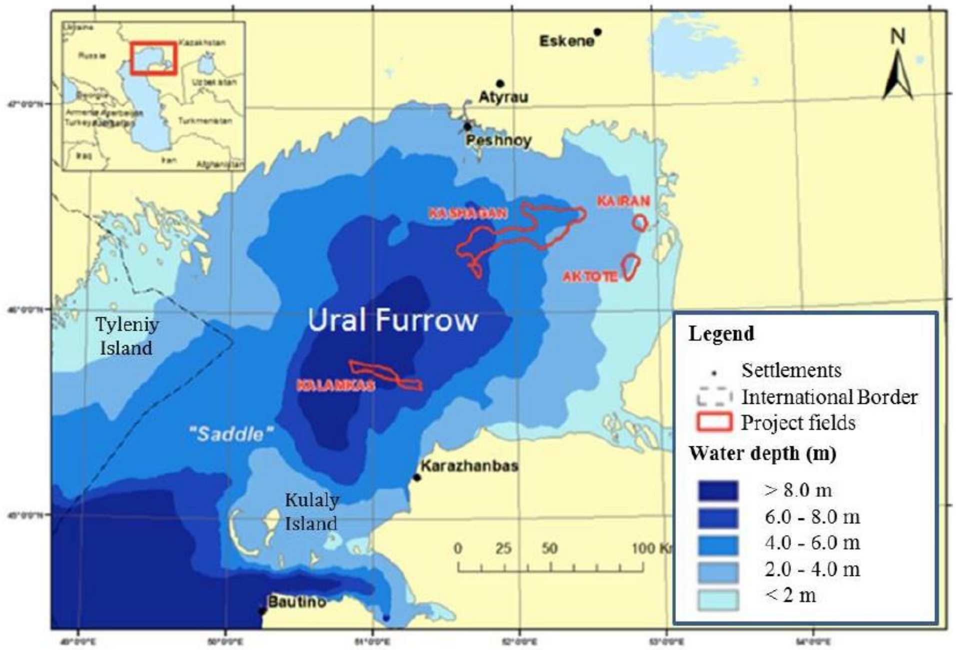

Figure 2.4 – Bathymetry chart of the Northern Caspian Sea.

Source: [42].

2.4. Wave conditions

One of the distinct features of the Caspian wave regime is the presence of ice that controls it during winter and spring periods. Waves move along the main wind directions – the SE and NW. As the water depth becomes shallow, the wave height starts to reduce in direction from east to the north. In the summer period, the waves barely reach 2-4 m because of the shallow water [39].

As you can see on the diagram (**Figure 2.5**), 96.9% of waves has a height up to 1.5 m, while the frequency of the waves with significant wave heights of 1.5-4.0 m is 2.6% per year. The wave length reaches up to 85 m at the southern border of the Northern Caspian Sea [33].

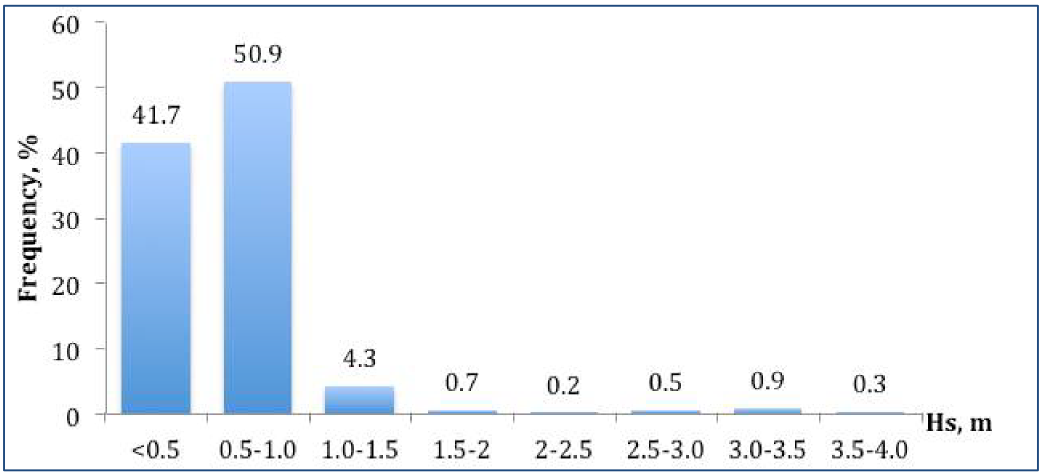

Figure 2.5 – Distribution of the significant wave height in the Northern Caspian derived from salinity altimetry for the period from October 1992 to December 2005.

Source: [22].

According to the **Figure 2.6**, the 50-year extreme wave height (return period, R_p = 50 years) can exceed 7 m at the border with the Middle Caspian Sea. The significant wave height with the 50-year return period reaches 1.0 m in the north-eastern part while it is equal to 2.5 m at the border with the Middle Caspian Sea [40].

a) Significant wave height with R_p=1 year;

b) Significant wave height with R_p =50 years;

c) Maximal wave height with R_p =1 year;

d) Maximal wave height with R_p =50 years;

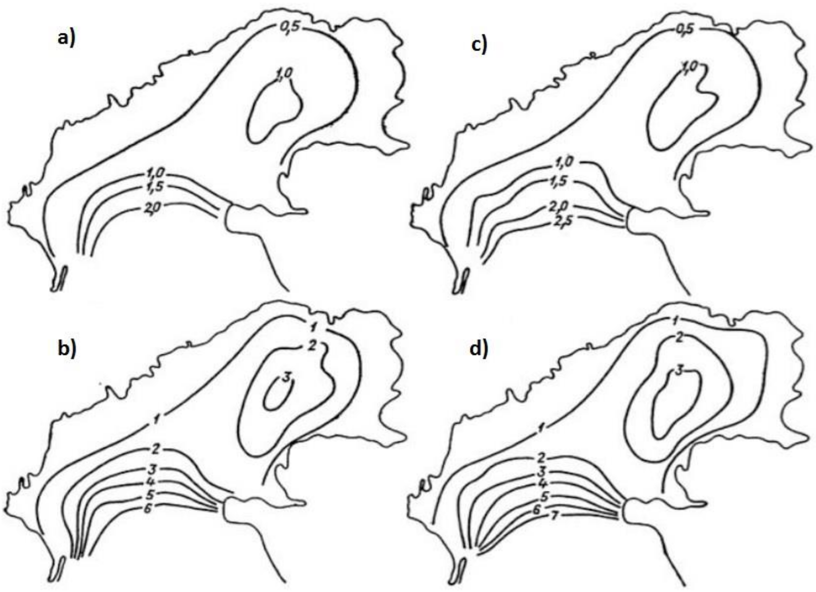

Figure 2.6 – Significant and maximal wave heights for different return periods. Source: [40].

2.5. Ice Conditions

Ice conditions are defined by the hydrometeorological situation in the Northern Caspian Sea.

Fields of interest are located in a zone of the fast ice. About 70% of the sea surface is covered by ice during winter (see **Figure 2.7**). Fast ice forms quickly and it remains until February/mid of March. The maximum thickness of sheet ice, with the probability of 1 time in 100 years, on the water area of the Filanovsky field is 0.98 m. Stamukha formation is possible (see **Figure 2.8**). The maximum thickness of the rafted ice is up to 120 cm. Steady ice formation on the water area occurs annually during the cold period. The start of ice-boom with formation of stratifications and ice ridges is in the middle of March due to the influence of gales. During the winter period, there is a possibility of waterworks frosting.

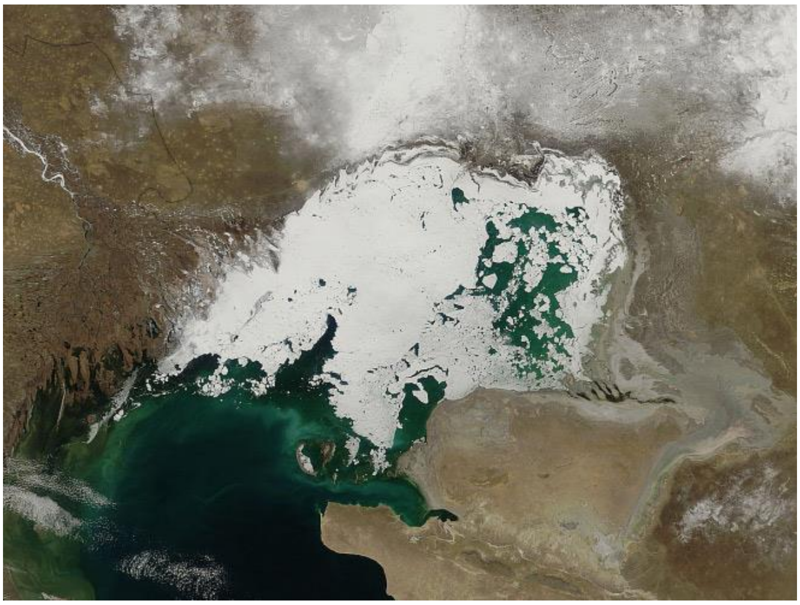

Figure 2.7 – Satellite image of the Northern Caspian Sea taken by NASA's Terra satellite, 2013.

Source: [57].

Figure 2.8 – Breaking Supply Vessel carrying goods in severe ice conditions of the Northern Caspian Sea, Kashagan field.

Source: [64].

Chapter 3. Scope of technology use

The scope of use includes fields in the Russian sector of the Northern Caspian Sea (see **Figure 3.1**) and can be expanded in the future to other sectors of the sea (Kazakhstan, Turkmenistan, Azerbaijan and Iran).

The Filanovsky oil field will be the main hub in the development, while other fields such as Kuvikin, 170 km and Rakushechnoe fields are considered as satellite fields. Korchagin field was the main hub before, but it changed its status to satellite in 2016 after Filanovsky field was put into operation. Therefore, in this thesis the whole development of the Russian sector will be considered as one field – Filanovsky cluster of fields.

Filanovsky oil field is located in the Northern part of Caspian Sea shelf 190 km South of Astrakhan as it is shown on **Figure 3.1**. It was discovered in 1994 and is operated now by Lukoil Company. The start of production was in 2016. Water depth in the area of production goes up to 11 meters. Main types of fluids include oil, associated gas, non-associated gas and gas condensate. Reserves are shown in **Table 3.1**. As it is the main hub and the core of the whole development it will be explained in more detail.

"The Yuri Korchagin field is located in the Russian waters of the North Caspian Sea at a sea depth of 11-13m. It is located 180km from the city of Astrakhan and 240km from Makhachkala. The field was discovered by Lukoil in 2000 and is owned by its subsidiary Lukoil Nizhnevolzhskneft. Its first oil was extracted on 28 April 2010. The proved, probable and possible hydrocarbon reserves in the Yuri Korchagin field are estimated to be 570 million barrels ($\sim 9.8 \times 10^7$ t) of oil equivalent" [58].

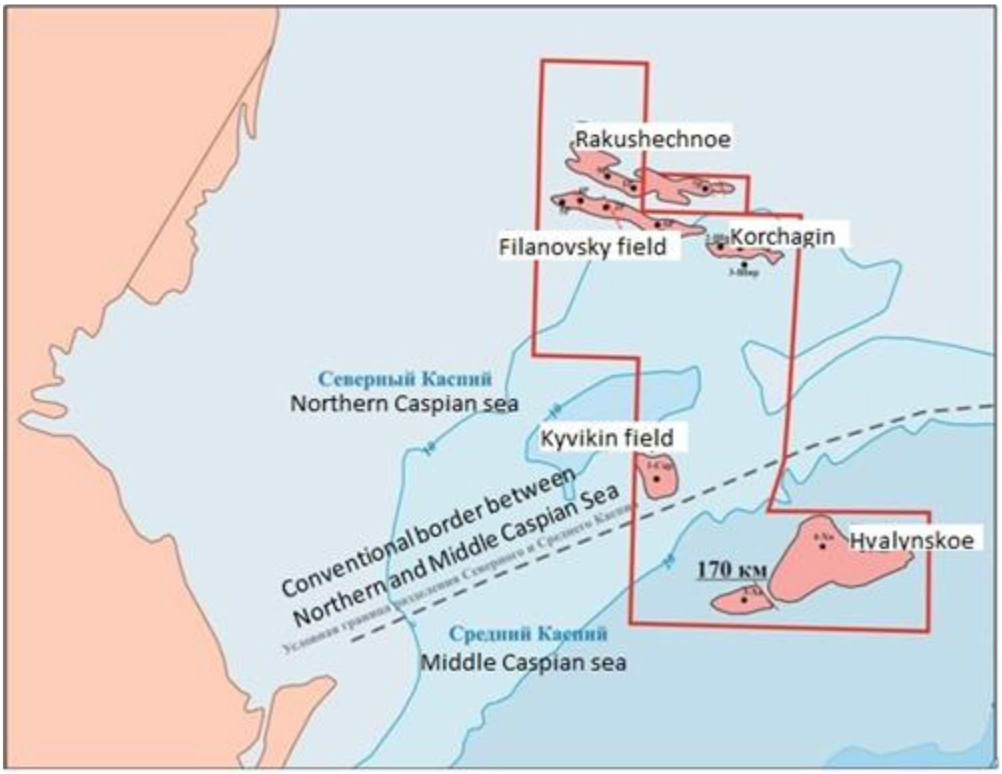

Figure 3.1 – Petroleum deposits of the Russian sector of the Caspian Sea. Source: [59].

Timeline:

- 2010 — Korchagin oil field was put into operation
- 2014 — First stage of Filanovsky oil field development
- 2016 — Hvalynskoe oil and gas condensate field was put into operation
- 2018 — 170 km field will be put into operation
- 2022 — Rakushechnoe field will be put into operation
- 2026 — Kyvikin gas condensate field will be put into operation

Table 3.1 – Oil, gas and gas condensate reserves of the Filanovsky cluster of fields (approximate values due to confidential information from LUKOIL).

	ABC1	C2
OIIP, ktons	500 000	200 000
Associated gas, MM m3	39 000	6 000
Non-Associated gas, MM m3	500 000	150 000
Condensate (initial), ktons	22 500	21 500

According to the enormous value of Filanovsky cluster of fields reserves, technology of this special vessel will have a great potential for use in this field.

The Filanovsky field includes three main reservoirs located in Albian, Aptian and Neocomian ages. These layers varies in reservoir properties and compound of middle porous sandstone facies with lamination of shale intervals. The cross-section of the field is shown on **Figure 3.2**. It is clear that the field is highly compartmentalized in South East part. Main reservoir properties are presented in **Table 3.2**.

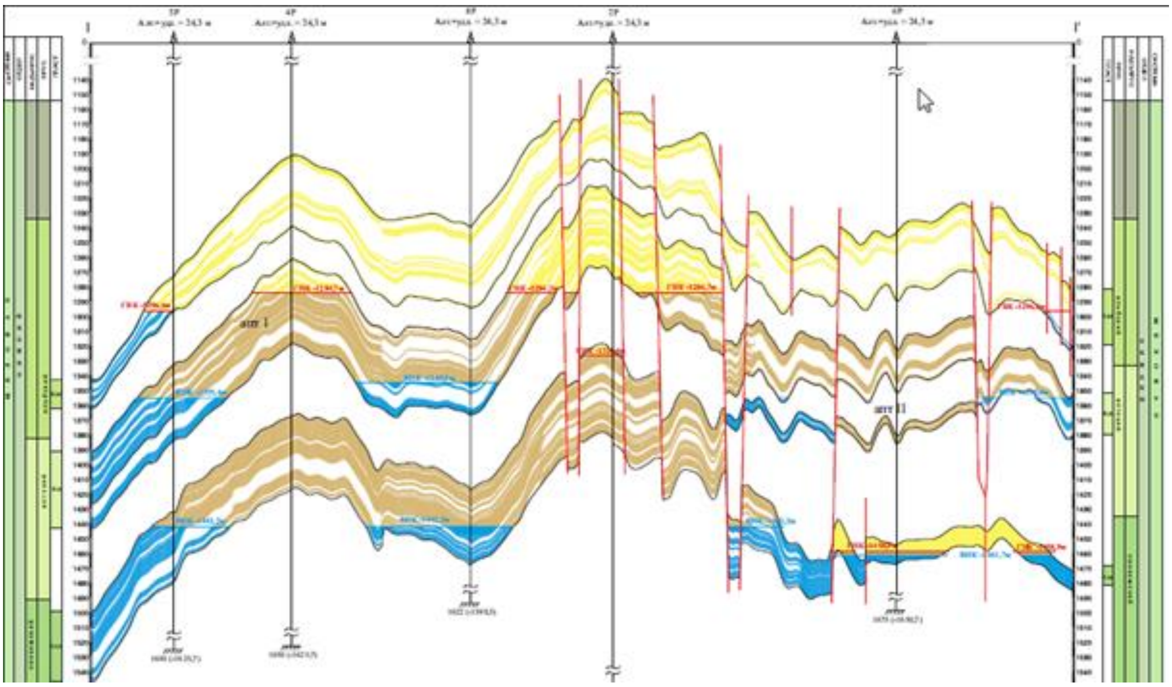

Figure 3.2 – Cross-section of the Filanovsky field.

Table 3.2 – Main reservoir properties of Filanovsky field (approximate values due to confidential information from LUKOIL).

Average porosity, %	20-24
Average HC saturation,	37-65
Net Pay, m	up to 50
Permeability, mD	0.5-600

The field will be developed in 3 stages. The 1st stage will be included the development of the West Neocomian reservoir and the 2nd and 3rd stages will include the development of Albian, Aptian and East Neocomian reservoirs. The horizontal drilling will be used to provide better sweep efficiency and higher productivity. The typical well placement is shown on **Figure 3.3**. Fields' infrastructure is described in the next chapter.

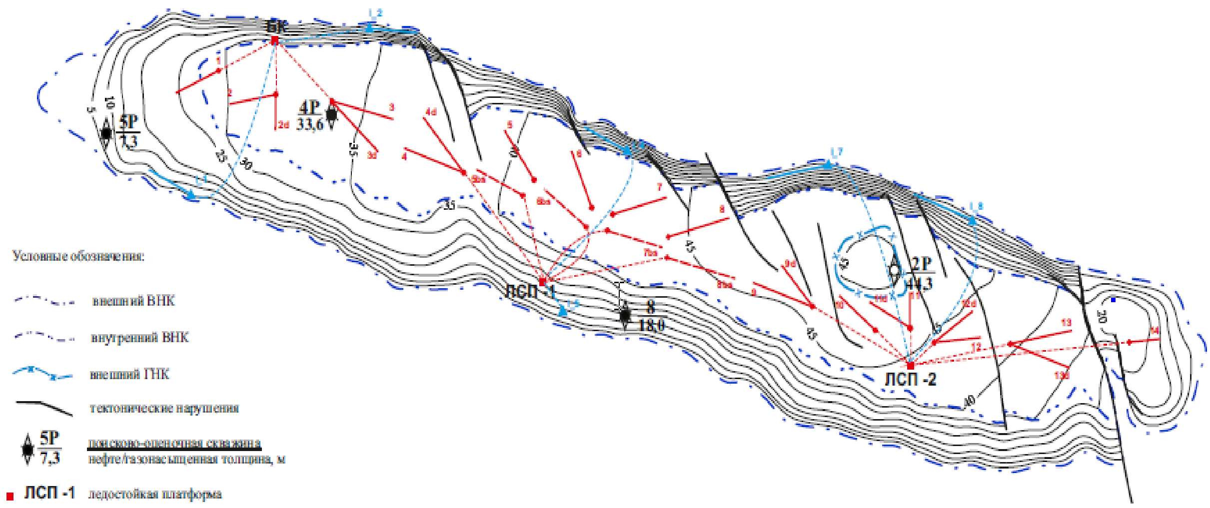

Figure 3.3 – Typical well placement for Filanovsky field (West Neocomian reservoir).

Chapter 4. Main objects of the Filanovsky cluster of fields infrastructure

As it was mention before the Filanovsky field is expected to develop in three main stages. The first stage will include the building of Ice-resistant fixed offshore platform (ЛСП-1 and ЛСП-2), living quarter platform (ПЖМ-1 and ПЖМ-2), central processing platform (ЦТП), wellhead platforms (БК). Ice-resistant fixed offshore platform ЛСП-1, living quarter platform ПЖМ-1, central processing platform ЦТП and riser block are already in place. Production from the field started in October 2016. The **Figure 4.1** shows all these facilities.

According to the figure, all fluids from satellite fields will go to the Filanovsky field by subsea pipelines and then to the coastline infrastructure.

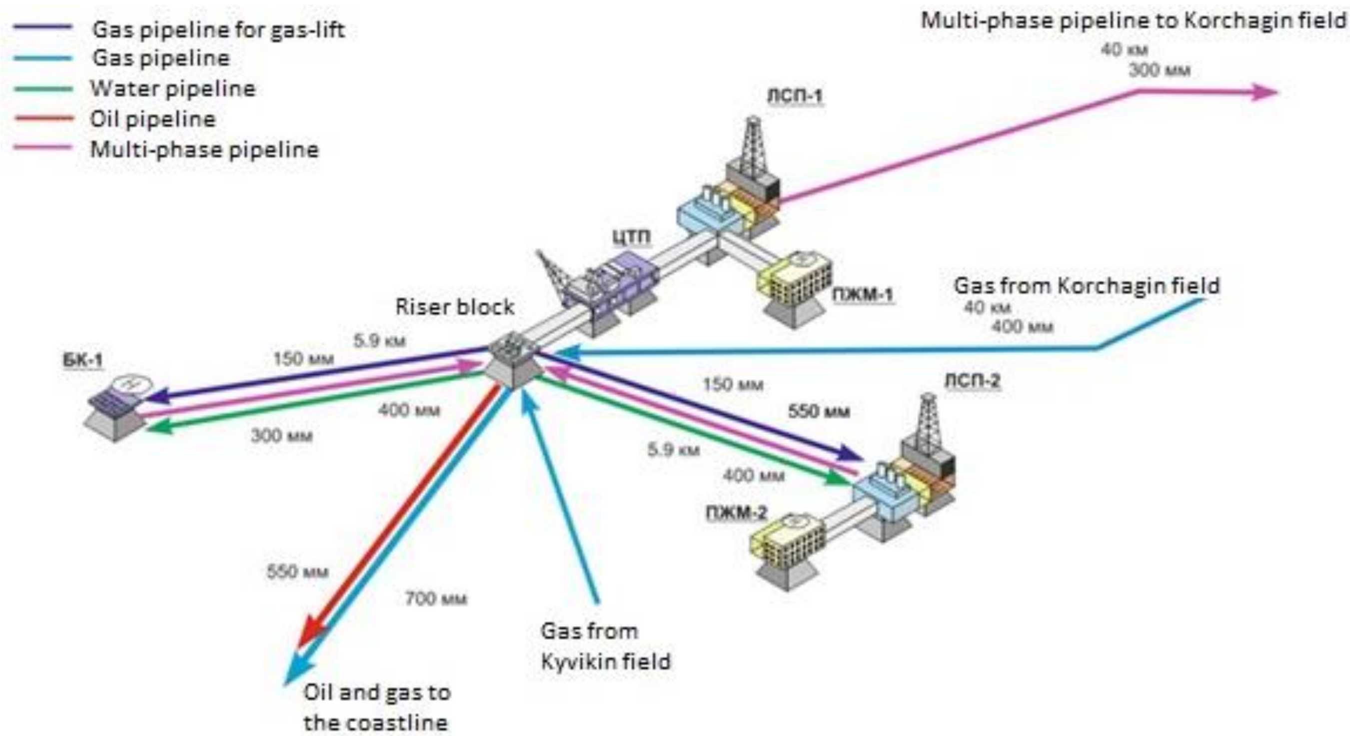

Figure 4.1 – The 1st stage of Filanovsky field development (based on pictures retrieved from http://isicad.ru/ and information from LUKOIL).

The 2nd and the 3rd stages will include the building additional facilities due to the increasing rate of production. These facilities include ice-resistant fixed offshore platforms (ЛСП-3 and ЛСП-4), living quarter platforms (ПЖМ-3 and

ПЖМ-4), central processing platforms for oil and gas (ЦТПН, ЦТПГ) and wellhead platforms (БК). It is demonstrated on **Figure 4.2**.

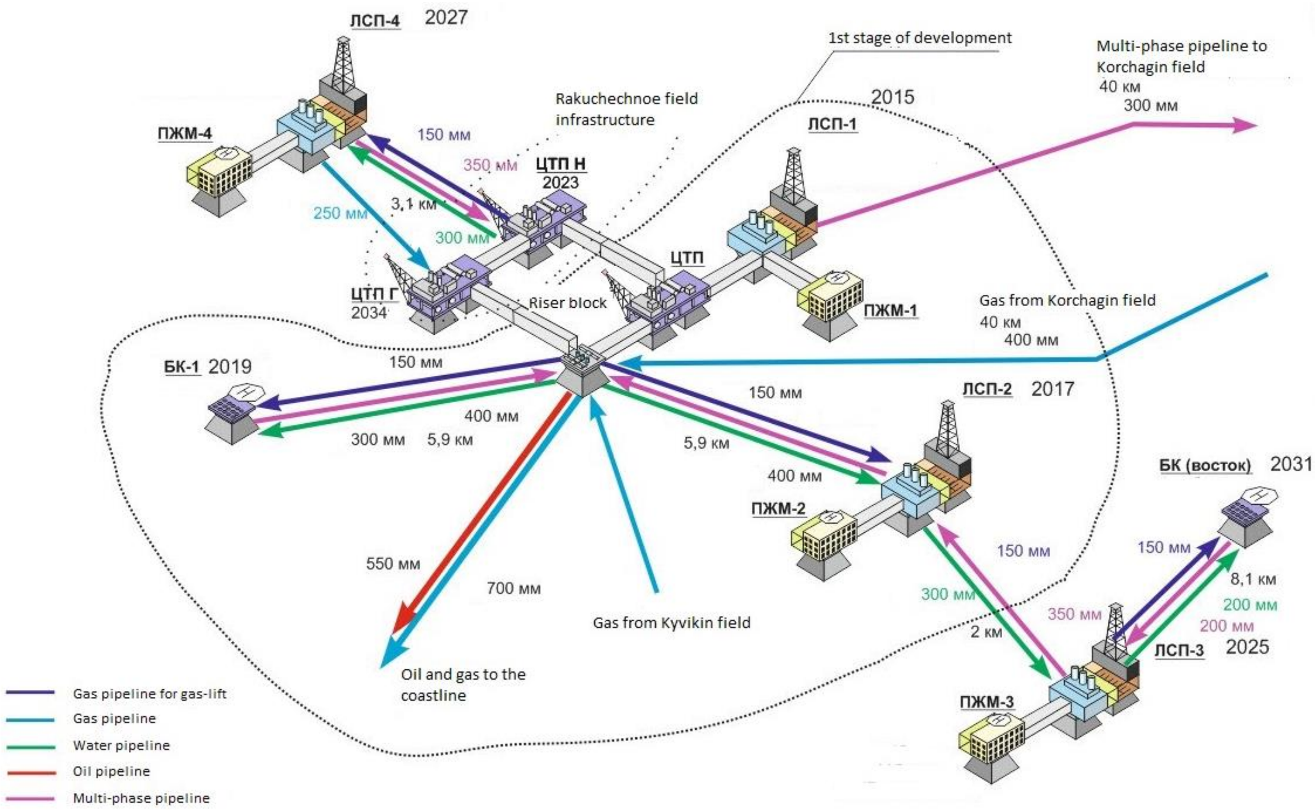

Figure 4.2 – The 2nd and the 3rd stages of Filanovsky field development (based on pictures retrieved from http://isicad.ru/ and information from LUKOIL).

Chapter 5. Technology concept of a vessel for hydraulic fracturing

As stated before an integrated approach for hydraulic fracturing and well interventions for offshore oil and gas fields includes three parts, first two of them are:

- The selection of the optimum vessel, that can be specially constructed or upgraded to carry all the equipment, that needed to ensure the successful down-hole works in challenging marine and ice conditions.
- The selection of the optimum technology for down-hole operations and deck equipment layout, based on the different characteristics of the formation and the well design.

First step for vessel selection is to make a list of vessels expected to be available during the required time window. After the list of available vessels is compiled, each vessel must be assigned a suitability rating. This rating can then be used to refine the broad list to a narrow pool of potential vessels [1].

To provide safe, reliable and successful offshore operation in the Northern Caspian Sea conditions the selected vessel should have the efficient size and free deck capacity, excellent stability and dynamic positioning system of at least 2nd class (DP 2, DP 3):

- Class 2 DP units should be used during operations where loss of position could cause personnel injury, pollution or damage with great economic consequences.
- Class 3 DP units with equipment class 3 should be used during operations where loss of position could cause fatal accidents, severe pollution or damage with major economic consequences and even sanctions.

DP 2 and DP 3 also means, that dynamic positioning system has redundancy so that no single fault in it will cause the system to fail [18].

In addition, for harsh winter conditions of the Northern Caspian Sea all operating vessels should be ice-resistant. Due to Russian Maritime Register of Shipping requirements, the vessel should be of at least Ice3 ice class to be allowed to move in the winter navigation season, which means that vessel can move independently in the sparse first-year ice of non-arctic seas with the thickness up to 0.7 m or can swim in the channel behind the icebreaker in level ice with the thickness up to 0.7 m. This class is almost equal to Ice Class 1A according to Finnish-Swedish classification.

All equipment should have High Safety Class due to conditions of the operating site (failure implies high risk of human injury, significant environmental pollution or very high economic or political consequences. Low safety class: minor environmental consequences and low risk of human injury. Normal safety class: for temporary conditions giving risk of human injury, significant pollution etc.) [19].

Hoses and coiled tubing used for this technology should be flexible and should withstand pressures up to 1000 bar during hydraulic fracturing operation. In addition, due to shallow water (ca 10m) hydraulic fracturing can be done only by the coiled-tubing without flexible risers, due to high bending radius of the flexible riser. Equipment for well interventions on the vessel deck must be perfectly fastened.

The economic efficiency of this method can be achieved by carrying out stimulation and intensifying of low permeability layers, resulting in significantly increased productivity, as well as enhanced oil recovery methods. Therefore, development of this technology and the special vessel for shallow water conditions is work of the great importance. This technology may also be in demand on the Arctic shelf of the Russian Federation, but with the use of an ice class vessel for the Arctic seas, so the work is of particular urgency for the Russian shelf.

Main advantages:

- Technology can increase economic efficiency in low-permeable offshore oil and gas fields;
- Technology will extend the life cycle of the well due to better well service;
- Technology can allow producing oil and gas from shales in offshore conditions;

- In global, technology can allow producing oil and gas from fields, which were previously considered as economically inefficient. This will result in creation of new workspaces, which in its turn will result in social stability and greater income for the government from taxes.

Main difficulties and operational limitations:

- Environmental conditions;
- Logistics according to vessel dimensions. This very important part is discussed in details in the Chapter 7.1;
- Very limited world experience, almost no experience in Russia (one established operation);
- Lack of technology;
- Large reservoir uncertainties;
- Low or even negative economic efficiency in offshore oil fields with high permeability, because of the need to shut in high productivity wells to carry the job, which results in huge money losses;
- Job can be carried out only in rather good weather conditions (not rough sea and huge ice concentrations);
- Pipes, hoses and coiled tubing should be specially constructed to carry extremely high pressures for hydraulic fracturing;
- Complex operation;
- Limited deck space;
- Equipment availability;
- Special vessel need to be constructed or already existing should be upgraded to carry all the equipment (pumps, coiled-tubing, reservoirs, blenders and etc.).

Chapter 6. World experience

In itself, offshore fracturing is a unique event. Only several operations in the world were executed.

6.1. Russia. Northern Caspian Sea

In Russia, hydraulic fracturing was conducted only by the “LUKOIL” in the Northern Caspian Sea in 2012 on the exploration well Rakushechnoe-8 (Rakushechnoe field, still in exploration phase), see **Figure 6.1**. The fracturing was executed successfully and resulted in a 20 times increased oil flow rate. Maximum liquid rate before the stimulation was about 4.8 m^3/day on a 6.4 mm choke size, after the stimulation it became about 108 m^3/day on a 9.5 mm choke size [12].

Figure 6.1 – Location of the Rakushechnoe field and drilling.

Source: [36].

The vessel selection for the job was a challenging problem. Special equipment was designed specially for this operation. The supply vessel “Vzmorye”, the only DP1 vessel (all other vessels were DP2) used for marine hydraulic fracturing operations, considered in this chapter (other parameters are in the Chapter 8) was upgraded and fitted with an additional deck to maximize available space for marine engineering and certification requirements, see **Figure 6.2** and **Figure 6.3** [36].

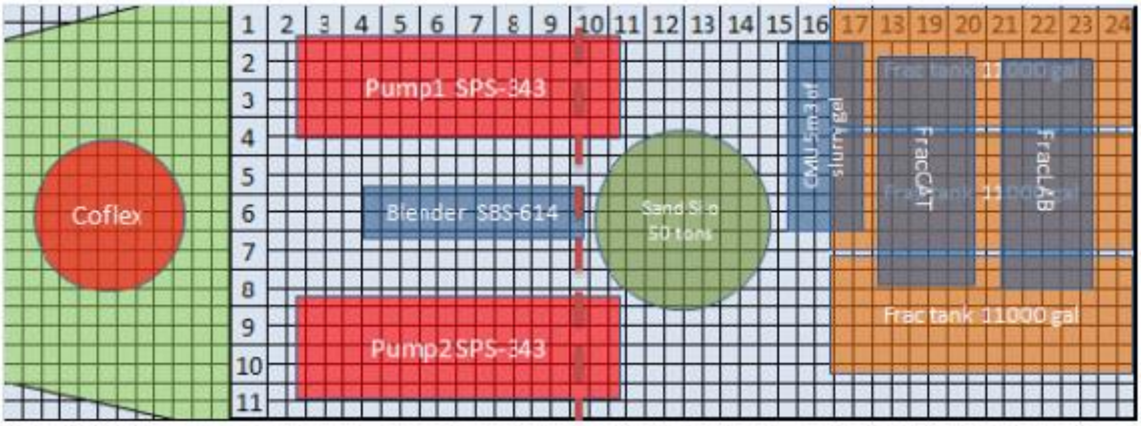

Figure 6.2 – Vessel deck layout (Vzmorye).

Source: [36].

Figure 6.3 – Photo of the vessel deck layout (Vzmorye).

Source: [36].

The economic efficiency calculations showed that implementation of marine hydraulic fracturing technology on most of the production wells for the Aptian reservoir of the Rakushechnoe field will significantly increase NPV15 of the field: negative without hydraulic fracturing, +193.6 mln $ with the technology (Duvanov et al, 2013).

6.2. UAE. Offshore Abu Dhabi

The offshore hydraulic fracturing operation was executed in the offshore Abu Dhabi. Fracturing equipment of high specification was arranged on the deck of the fracturing vessel and testing equipment was installed on the deck of the jack-up rig. This was done, because hydraulic fracturing was executed right after the well completion. Job was provided in the HPHT (High pressure, high temperature) conditions of the reservoir, that caused variety of challenges and made this offshore hydraulic fracturing the first HPHT offshore hydraulic fracturing in the Middle East.

Three-stage hydrofracturing was performed successfully and the measured gas rate was five times higher than without hydraulic fracturing. The fracturing equipment layout on the DP2 (no other information about the used vessel in open sources) vessel deck is presented on the **Figure 6.4**. This type of vessel was chosen due to its stability under the wind speed of up to 18 m/s [1].

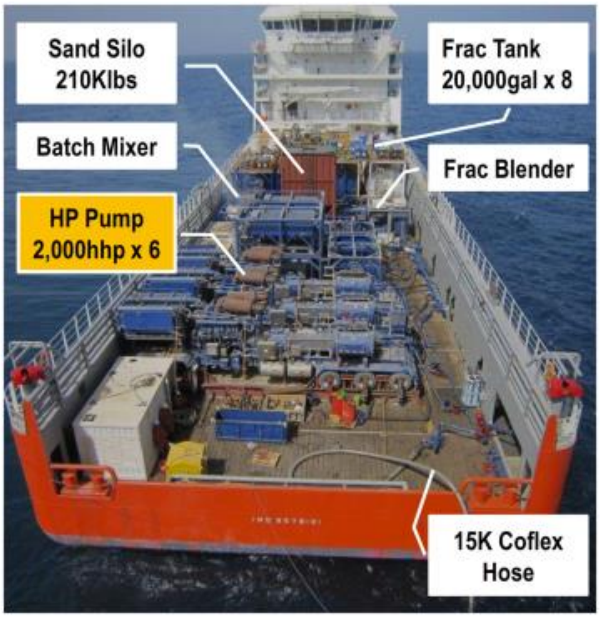

Figure 6.4 – Photo of the vessel deck layout (Abu Dhabi).

Source: [1].

6.3. India. Krishna Godavari Basin

The offshore hydraulic fracturing was performed in the Krishna Godavary (KG) Basin – the main basin at East coast of India (see **Figure 6.5**). This method of enhancing oil recovery was needed due to extremely tight nature of the formation, so fracturing was an essential technique of production well completion. Fracturing was challenging also due to extremely tough HPHT conditions of the field. Considered field Deen Dayal East is situated on the eastern side of Kakinada coast in Andhra Pradesh with water depth at 100m [2].

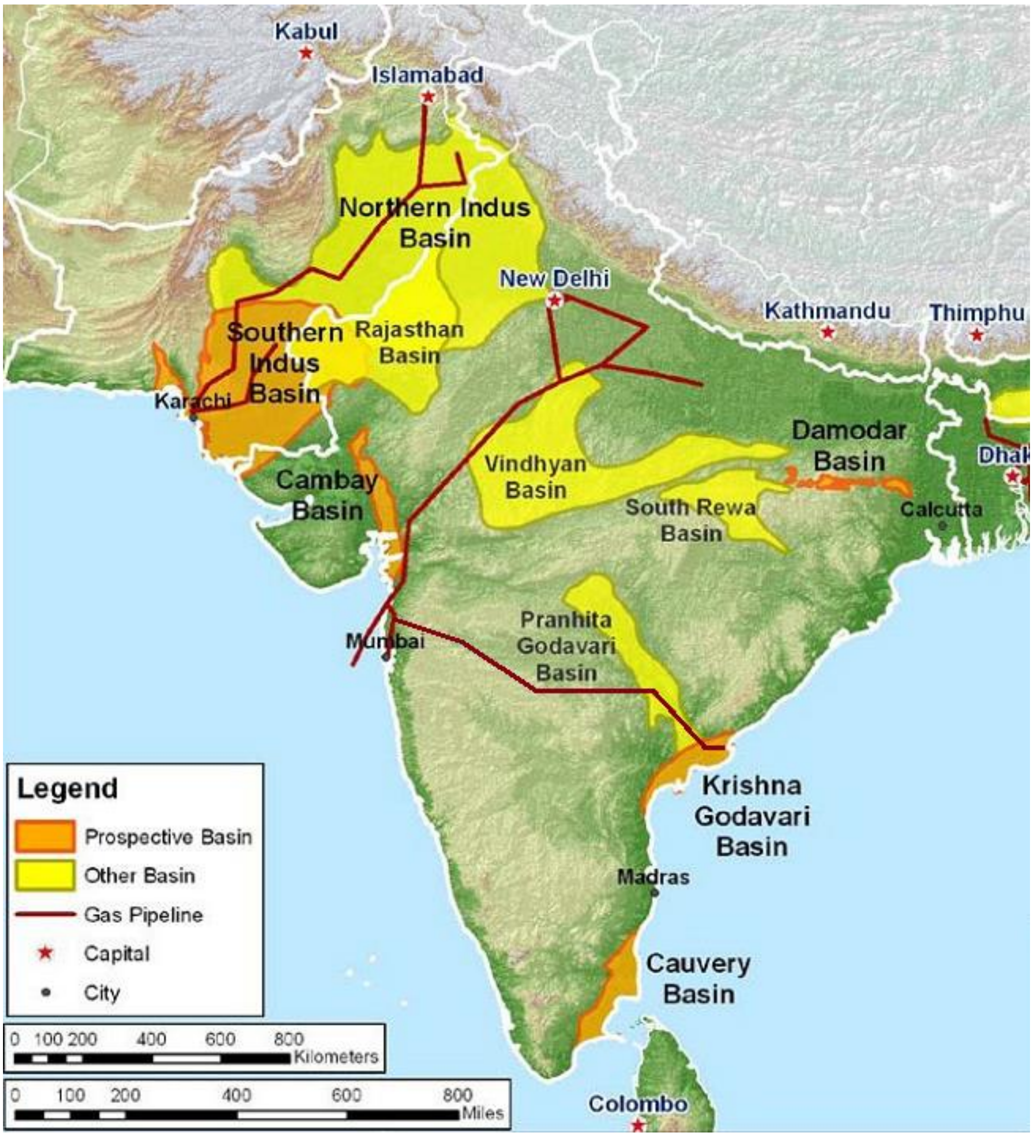

Figure 6.5 – Krishna Godavari Basin location.

Source: [65].

Among three examples considered in this chapter, this is the only one, when operation was executed from a jack-up rig. Deck dimensions are presented on the **Figure 6.6** and fracturing equipment layout is shown on the **Figure 6.7** [2]. Unfortunately, data about the gas flow increase and economic efficiency were not presented in the paper and open sources.

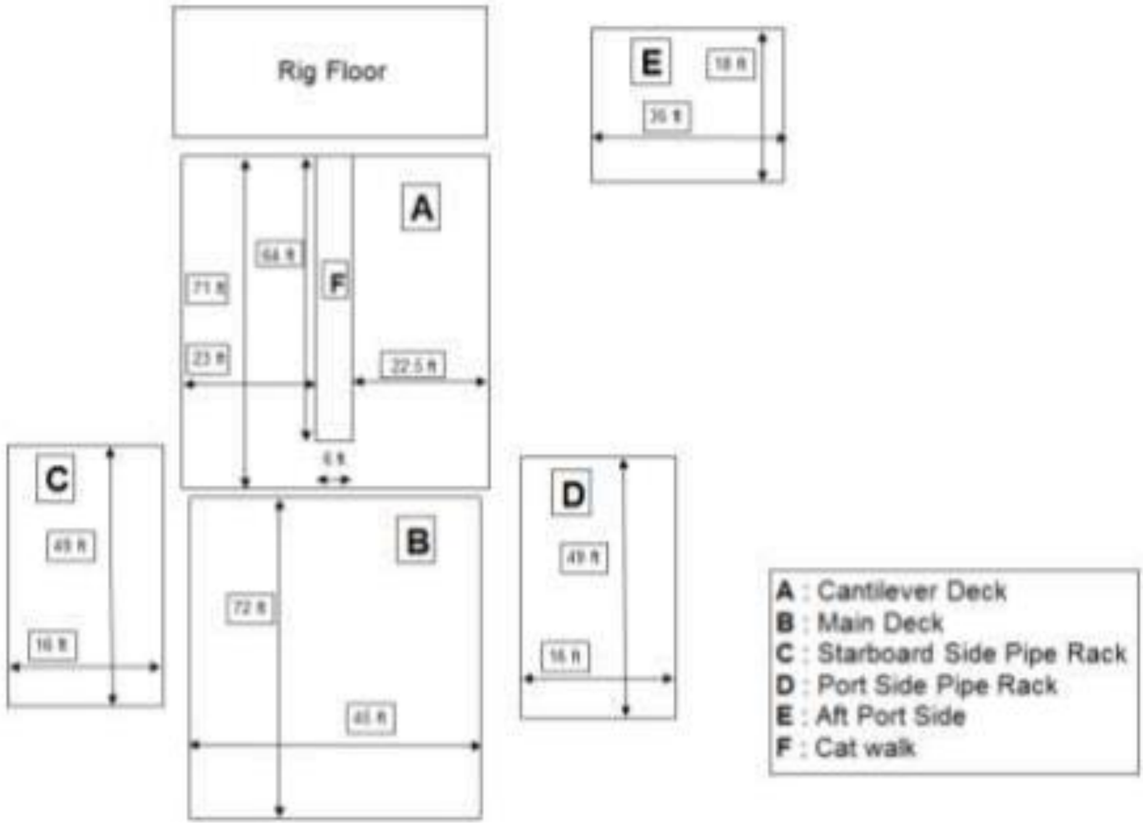

Figure 6.6 – Dimensions of cantilever and main decks on jack-up rig.

Source: [2].

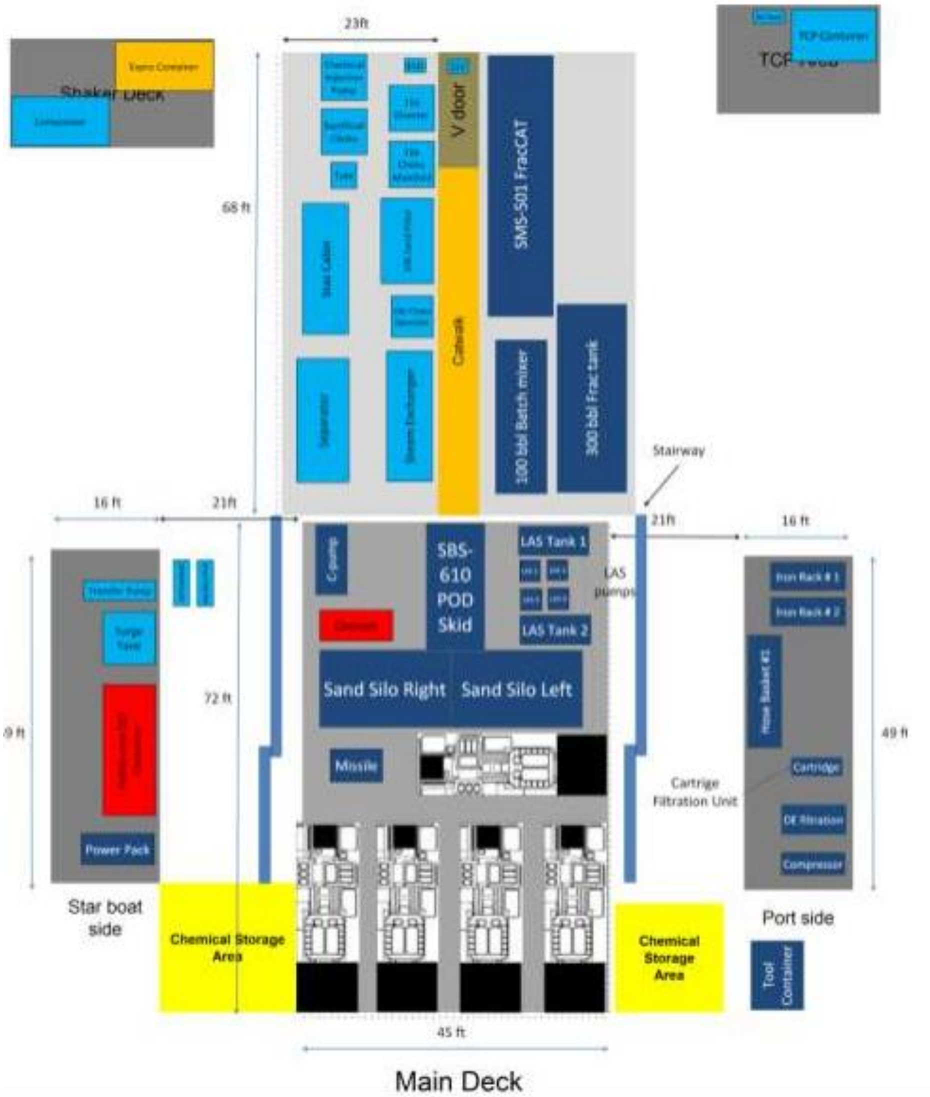

Figure 6.7 – Fracturing equipment layout (Krishna Godavari basin).

Source: [2].

6.4. Baker Hughes twins

The Baker Hughes company has two twins of the new generation of supporting vessels – Stimulation Vessel. These twins are called Blue Dolphin and Blue Orca.

"The Baker Hughes Blue Dolphin dynamically positioned well stimulation vessel (see **Figure 6.8**) is equipped with 20,000-psi (137.9-MPa) maximum working pressure pumps and treating lines. It carries three flexible steel umbilical lines that allow up to 80 bbl/min (0.21 m3/s) pumping rates and is supported by 23,000-

hydraulic horsepower pumping capacity. These capabilities, combined with the vessel's storage capacity, enable the completion of multiple well treatments on a single voyage without the need to return to dock to resupply" [47].

Figure 6.8 – Baker Hughes Blue Dolphin.

Source: [47].

"The Blue Orca stimulation vessel houses five Baker Hughes Gorilla™ pump units, each one capable of delivering 2,750 HHP. The two fluidend sizes can be reconfigured quickly and easily to provide maximum flexibility. The Blue Orca can carry 2.5 million lb. (1134 tons) of sand or equivalent proppant—allowing it to perform multiple fracturing treatments without having to return to port to resupply.

Advanced systems permit smooth, efficient, and reliable blending of high-quality fracturing fluids and eliminate the need for oil-based slurried polymer concentrates. An industry-leading, three-mode acid- blending system provides safe, reliable, and highly versatile mixing of a wide range of organic or inorganic acid systems. Eight lined tanks hold a total of 180,000 gal (681,374 liters) of organic and inorganic acids and solvents for maximum flexibility and reliability while meeting or exceeding all safety and environmental standards" [47].

Vessels of this type can be a perfect solution for the hydraulic fracturing in the Northern Caspian Sea region, but due to the absence of ice class, that restricts execution of the operation during winter season, and relatively large draft (7.3m) it is impossible to get vessels of this type to the Caspian Sea and use Blue Dolphin and Blue Orca for the job execution. Vessel dimensions limiting criteria are considered in the next chapter.

Chapter 7. Optimum vessel selection and analysis

Vessel selection for this technology execution is a complicated task.

7.1. Technical limiting criteria.

- Vessel dimensions, logistics.

These parameters are the most important not only due to the water depth on the operation site, but also due to very complex logistics. The Caspian Sea is an endorheic basin, other words an enclosed inland body of water, that is why it is usually classified as the biggest lake in the world. The only way to get there is through a large net of rivers and channels - Unified Deep Water System of European Russia. There are only two ways for big vessels to get to the Caspian Sea: Volga-Baltic Waterway and Volga-Don canal from the Black Sea. Parameters of these two waterways such as guaranteed water depth, height of bridges and lock dimensions are the limiting criteria for the ship size.

Maximum allowed vessel size in Volga-Don canal is 140 m long, 16.6 m wide and 3.5 m deep, which is called the Volga–Don Max Class [60].

Volga-Baltic waterway has a guaranteed water depth 4m, which makes risky sailing of ships with higher draft. The locks' limiting dimensions are 210 m long, 17.6 m wide and 4.2 m deep [61]. In addition, dimensions of a vessel are limited by the height of bridges. Minimum value of this parameter is 16.1 m [62]. Therefore, these parameters are parameters of the biggest ship, which is allowed to go through Volga-Baltic waterway.

According to this, Volga-Baltic waterway was chosen the best suitable logistic path for the vessel due to the larger locks' parameters, height of bridges and water depth.

- Free deck area and maximum deck loading.

Fracturing, acidizing and well service equipment is very volumetric and heavy. Due to this fact, free deck area is very essential for the operation. All techniques should be installed within this area. Maximum deck loading is a limitation criterion for the weight of the equipment, and is measured in ton/m^2. Equipment layout depends on both of these factors that is why the optimum vessel selection should be made very properly in order to place all equipment on the deck and not to cause instability of the vessel during operation.

- Ice, wind, currents and wave conditions.

All environmental criteria such as wave spectrum, wind speed, currents and ice concentrations should be properly estimated during operation design.

Vessel with the suitable ice class and dynamic positioning system should be selected for the operation.

- Open stern for deployment of high-pressure hose;

7.2. Other limiting criteria.

- HSE (Health, Safety and Environment);
- Compliance with local state restrictions and government regulations regarding vessel flagging and cabotage laws;
- Equipment and vessel availability for the required time window.
- Infrastructure existence;
- Sufficient beds available for the pumping crew and company representative;
- High sidewall protection to insulate the crew and equipment from rough seas;
- Crew experience;
- Management level.

7.3. Vessel comparison

Six vessels were compared in the thesis.

<table>
<tr>
<td>
“MSV Ocean Intervention”
(Retrieved from http://www.oceaneering.com)</td>
<td>

“Vzmorye”
(Retrieved from http://korabli.qdg.ru/photo/view)</td>
<td>
“Arcticaborg”
(Retrieved from http://arctech.fi/ships)</td>
</tr>
<tr>
<td>

“Blue Dolphin”
(Retrieved from www.bakerhughes.com)</td>
<td>

“Damen Platform Supply Vessel 1600”
(Retrieved from http://products.damen.com/)</td>
<td>
“Bourbon Arethuse”
(Retrieved from www.bourbonoffshore.com)</td>
</tr>
</table>

Parameters of vessels are in the **Table 7.1**. Red color – not suitable parameter, which excludes vessel from the further comparison. Green color – advantage in comparison with others. All data is retrieved from the manufacturers' websites (in references) [47, 48, 49, 50, 51, 52].

Table 7.1 – Vessel parameters comparison.

Parameters	"MSV Ocean Intervention"	"Vzmorye"	"Arcticaborg"	"Blue Dolphin"	"Damen Platform Supply Vessel 1600"	"Bourbon Arethuse"
Length	243 ft/74.07 m	65 m	65.1 m	Blue Dolphin is a special stimulation vessel with all equipment already installed onboard. This is the best choice for deep-water projects. However, in this project it was considered only briefly and was eliminated because of a very big draft (7.3 m), that is not suited for shallow waters of the Filanovsky and Korchagin fields. It's also impossible to	60.8 m	58.7 m
Beam	53.5 ft/16.15 m	15 m	16.6 m		14 m	15.6 m
Depth mld.	18.8 ft/5.49 m	6.2 m	4.4 m		6 m	6 m
Draft	Max 15 ft/4.57 m	Max 4.3 m	Max 2.9 m		Max 5 m	Min 3.5 m Max 5 m
Deadweight at max draft	2320 t	980 t	650 t		1600 t	1413 t
Deck area	5454 sq. ft/507 m^2	340 m^2	350 m^2		390 m^2	377 m^2
Deck load capacity	7323.6 kg/m^2	No data	5 t/m^2		Deck cargo: 500 t Deck load t/ m^2: No data	Deck cargo: 300 t Deck load: 5 t/ m^2
Speed	10 knots	13 knots	13 knots 3 knots (60cm ice)		12.3 knots	Maximum 13 knots Service speed: 10 knots

DP	DP 2	DP 1	DP 2	transport this ship through both Volga-Baltic waterway and Volga-Don canal to the Caspian Sea. Also the deepest port in the Russian sector of the Caspian Sea has 5m depth. It makes impossible for the vessel to get to the port.	DP 1 (DP 2 optional)	DP 2
Ice class	NO	Ice3	1A Super		NO	NO
Propulsion power	6000 hp/4.4 MW	Total power: 7178.8 hp/5.28 MW	3.24 MW		3 MW	3.6 MW
ROV carrier	YES	NO	NO		NO	NO
Tanks capacity	Fuel Oil: 800 m^3 Lube Oil: 19 m^3 Ballast: 1600 m^3	Fuel Oil: 650 t Ballast: 467 t	Fuel Oil: 363 m^3 Liquid mud: 48 m^3 Fresh water: 278 m^3 Bulk: 51 m^3 Cargo sewage: 67 m^3		Fuel Oil: 220 m^3 Ballast Water: 570 m^3 Potable Water: 240 m^3 Liquid Mud: 390 m^3 Drill Water: 400 m^3 Fuel Oil Cargo: 430 m^3 Dry Bulk: 170 m^3	Fuel Oil: 612 m^3 Ballast: 151 m^3 Antiheeling: 226 m^3 Fresh water: 427 m^3 Dispersant: 17 m^3 Foam: 20 m^3
Crew Accommodation	No data 50	No data	12 20		15 19	No data 46
Crane capacity	40 ton	No data	No data		No data	1.5 t, 15 m
Features and Comments	• Two Large Moonpools • 60 T Stern A-frame • Maximum® Work Class ROV	Was used for the first offshore hydraulic fracturing in Russia in the Northern	• Ice-breaking supply vessel. • Is already in the Caspian Sea supplying Kashagan field in Kazakhstan.		"Damen Technical Cooperation enables you to build your Damen vessel locally, anywhere in the world. We will provide you with a prefabricated shipbuilding kit and can, on	

	• Onboard ROV Tooling Suite • Modular Equipment Options • Satellite Communications Equipment System for Transmitting Streaming Video of Real-Time Work to Shore Personnel	Caspian Sea. Main benefit in comparison with others except Blue Dolphin – crew and company already have experience.	• Was built in Finland and transported to the Caspian Sea by Volga-Baltic Waterway.		request, combine this with expert assistance, training and backup. By using standardised components it is possible to make a custom-built design, fulfilling any specific local requirements. This cost-efficient technique can be applied to the full range of Damen vessels across a wide variety of marine operations. One in five Damen vessels is built locally on-site by Damen Technical Cooperation" [49].	

Main parameters for consideration: vessel dimensions, ice class, dynamic positioning system, deck area and tanks capacity. Already existing tanks can carry fracturing fluids, so we have more free space on the deck, because we don't need to install additional tanks there.

It should be noted, that Damen Shipyards Group provides a unique offer for clients. Their technology of supplying with a prefabricated shipbuilding kit and local construction is a very good solution for enclosed/inland waters such as Caspian Sea or even inaccessible locations, when sometimes it is not possible to deliver a vessel ex-yard. These vessels can be constructed almost on every yard in the world and make the logistics easier and more flexible, because containers can be transported by trains on land, by planes or smaller vessels. In addition, this vessel has the biggest volumes of tanks capacity, that can be used for storage of chemicals and proppant, but due to absence of ice class it was excluded from further consideration.

According to the comparison table, only two vessels passed the necessary requirements for the whole year operation: Vzmorye and Arcticaborg. Nevertheless, the best suitable vessel that can be easily transported to the operation site is Arcticaborg type due to maximum draft equal 2.9 m. Other vessels were deemed unsuitable. Arcticaborg and her sister Antarcticaborg already recommended themselves by operation on the Kashagan field for several years. The best suitable vessel for operation without ice only during middle spring-summer-early autumn navigation is MSV Ocean Intervention. Even if it has the maximum draft 4.57 m, minimum draft without any equipment is around 3.5 m, so it will pass all locks in the Volga-Baltic Waterway and will get to the Caspian Sea.

Arcticaborg has all necessary fluid and bulk tanks and perfect draft for shallow water conditions in comparison with other vessels. It is also supplied with good dynamic positioning system DP2 and has Ice class 1A Super according to Finnish-Swedish classification, which is perfect for winter conditions of the Northern Caspian Sea.

In addition, Arcticaborg can operate in waters covered with sparse ice with thickness up to 90 cm. All calculations according to the sailing in unbroken level ice are given in the Chapter 10.2 – Resistance of ships in unbroken level ice. Thus, the final recommendation is **Arcticaborg**.

Chapter 8. Ship motions

Ship motions are very important and characterize vessel's behavior during operations, maneuvering, station keeping, cargo transportations or crew comfort.

Vessel motions can be defined by the six degrees of freedom (DOF). The six DOF motions are separated into three translational and three rotational motions (see **Figure 8.1**).

Translational motions include:

- Surge (moving forward and backward);
- Sway (moving left and right);
- Heave (moving up and down along the vertical axis).

Rotational motions consist of:

- Roll (pivots side to side);
- Pitch (tilts forward and backward);
- Yaw (swivels left and right).

The importance of each of the six DOF in offshore operations is different and depends on the type of operation [16].

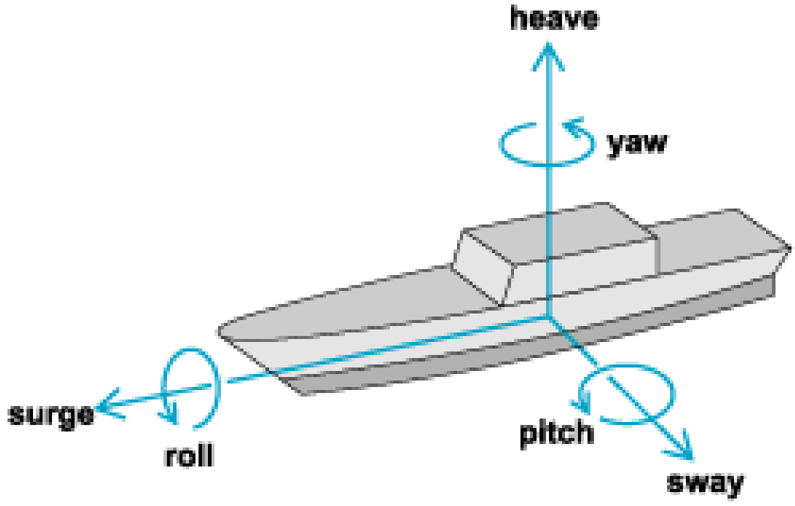

Figure 8.1 – The six DOF for vessel motions.

Source: [16].

The rotational motions (roll, yaw and pitch) are the same for all points of the vessel, while the translational motions (heave, surge and sway) are coupled and depend on the motions of the other degrees of freedom. In the thesis most of the attention is paid to roll and heave, other parameters also affect operations execution but have less effect [16].

The main aim for vessel motions' analysis is to avoid undesirable significant motions that are caused by the resonance. Resonance occurs when the natural period of a vessel is equal to the actual sea state period. To predict the vessel motion in waves we should calculate the response for every load frequency for all DOF.

Hydrodynamic forces in regular waves are divided into two sub-systems [13]:

- Forces and moments acting on the ship, when the structure is restrained from oscillating and is subjected to regular waves. These hydrodynamic loads are called wave excitation loads or forces and consist of Froude-Krylov forces and diffraction forces.

- Forces and moments acting on the ship, when the structure is forced to oscillate with the wave excitation frequency in any rigid-body motion mode in still water conditions. The forces are divided into added mass, damping forces and restoring forces.

Due to linearity, the obtained forces can be summed to get the total hydrodynamic force.

Let us discuss forces acting in still water conditions in more detail.

Added mass.

The added mass (AM) is a steady-state hydrodynamic force due to forced harmonic rigid body motions. The added mass is water particles that move due to the movement of the vessels on its wet surface. The AM is determined by calculations and depends on the hull form. It can be found from model test or by actual field measurements of vessel behavior. To simplify calculations we can use the assumption, that the volume of added mass is equal to half a cylinder under the vessel [16].

Damping forces.

The main contribution to ship damping is the damping caused by radiated waves. Heave motions are heavily damped by radiation damping, which is the dissipation of energy through waves being generated by the vessel's movements. Roll damping is mostly due to viscous effects [34].

Restoring forces.

Restoring forces take place due to bringing the buoyancy and weight equilibrium out of balance. Relative change in the buoyancy force is associated with the vessel waterline zone.

Heave and roll motions are described by the following equations, using the parameters mentioned above. Symbols used in the equations are given in the **Table 8.1** [16].

Table 8.1 – Symbols and units used in heave and roll motions equations.

	Position	Velocity	Acceleration
Translational motion (heave)	$z(t)$	$\dot{z}(t)$	$\ddot{z}(t)$
Rotational motion (roll)	Angle $\theta(t)$	Angular velocity $\dot{\theta}(t)$	Angular acceleration $\ddot{\theta}(t)$

The equation of motion in heave is given by:

$$M\,\ddot{z}(t) + c\,\dot{z}(t) + k\,z(t) = F(t) \tag{8.1}$$

Where:

M – Total mass, $M = m_{vessel} + m_{added}$;

c – Damping coefficient in heave;

k – Stiffness.

The solution is:

$$z(t)=z_h(t)+z_p(t) \quad (8.2)$$

Where:

$z_h(t)$ is the solution of the homogeneous equation,

$$M\,\ddot{z}(t)+c\,\dot{z}(t)+k\,z(t)=0\;; \quad (8.3)$$

$z_p(t)$ is a particular solution of the full equation (8.1).

The equation of motion in roll is given by:

$$I_T\,\ddot{\theta}(t)+c_r\,\dot{\theta}(t)+k_r\,\theta(t)=M(t)-moment\,of\;\;force \quad (8.4)$$

Where:

I_T – Transverse mass moment of inertia;

$k_r\theta(t)$ – Uprighting moment;

c_r – Damping coefficient in roll.

Chapter 9. Stability

9.1. General terms and information

Stability of vessels is a parameter of utmost importance to ensure safe operations. All operations on the design stage should meet the minimum requirements for stability to protect the vessel from the danger of capsizing.

"Basic theory of ship stability is given by the metacentric height and stability curves. Metacentric height is considered for the static stability, and the stability curves are considered for the dynamic stability of the vessel".

A ship experiences upsetting forces causing instability, which are [34]:

- Beam wind;
- Waves;
- Lifting over the side;
- High-speed turns;
- Icing;
- Grounding;
- Shifting of weights within the ship;
- Entrapped water on deck;
- Free surface moments.

Assumptions in simplified stability calculations:

- The water is incompressible;
- No viscosity;
- No surface tension;
- Plane water surface.

Assumptions decrease the accuracy of the final calculations. However, using of them can help us to derive general results and evaluate key properties of a vessel.

Arcticaborg has a large capacity of initial tanks, for operations additional tanks will be installed on the deck, which will affect the stability. During operation the level of liquids in tank will be rapidly decreasing, due to pumping into the well to stimulate the formation. Too fast change in total weight of the vessel can cause instability.

Another concern is the liquid motion in tanks during the roll, which is called the free surface effect. It should be taken into consideration; the crew should always monitor the reduction of fluid level in tanks. One of the solutions is to make separate sections in tanks and reduce the area for fluid motions and fluid moment of inertia in half-filled tanks in order to maintain the center of gravity (COG) as near as possible to the initial condition (see **Figure 9.1**).

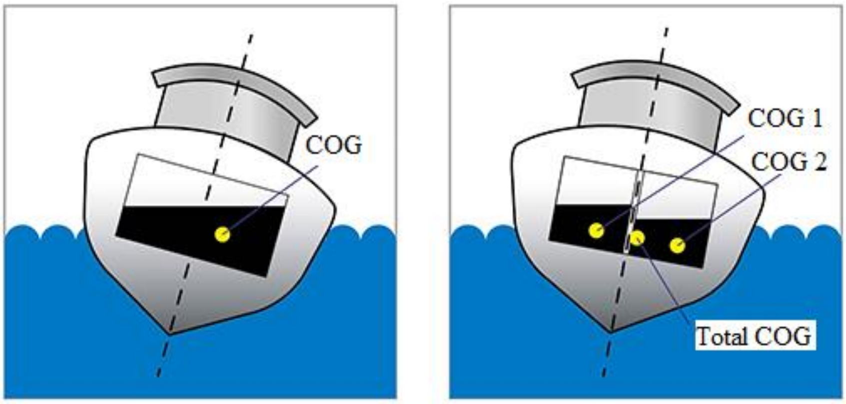

Figure 9.1 – Free surface effect problem solution.

Source: [66].

In our case, Arcticaborg with equipment is a top-heavy vessel, so it can get unstable. Solution for this problem can be to lower center of mass by ballast or installation of heavy keel. Other causes of vessel instability are rough sea conditions, icing, wrong load and lack of crew experience.

It is vital to analyze stability for any possible loading condition of a vessel, especially for stimulation vessels, which meet very different loading situations during operations execution. Chapter 9.2 will describe initial stability analysis, while in the Chapter 9.3 we will discuss hydrostatics of the ship and cross curves of stability calculations made in the Free!Ship software.

9.2. Initial stability

9.2.1. Initial stability theory

Initial stability is the stability gained in case of a small deviation from the original position. In addition, it can be described as a vessel's ability to return to the original position in case the upsetting force has gone away [16].

Initial stability is checked for a ship with regard to freeboard, transverse stability and longitudinal stability.

$$Freeboard = H - d \tag{9.1}$$

Where, H – height and d – draft. Free board limit to the amount of ballast and cargo should be always checked.

Static stability is stated in terms of the initial metacentric height, GM.

$$GM = KB + BM - KG \tag{9.2}$$

A ship is considered to be initially stable if the initial metacenter is above the center of gravity, other words when GM > 0 [17]. See **Figure 9.2**.

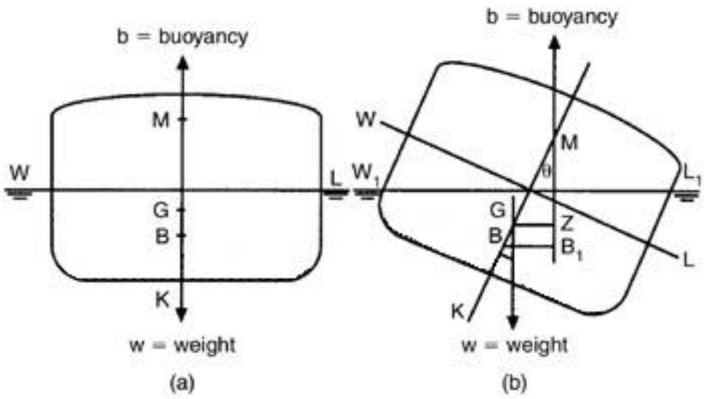

Figure 9.2 – Stability without (a) and with a small angle of heel (b).

Source: [67].

DNV GL (Norway) requires initial GM>0.15m as an intact stability criteria for ships [10]. Russian Maritime Register of Shipping requires initial metacentric height GM to be not less than 0.15 m, while the corrected initial metacentric height of ships in the loaded condition, with icing disregarded, shall not be less than 0.2 m. [30]. As operation is carried out in Russia, it will be considered as a minimum value.

The freeboard at the stern in the upright condition according to the DNV GL shall not be less than 0.005 times the ship's length in any loading condition [9]. The same requirements are according to the Russian Maritime Register of Shipping [30].

BM is the distance from center of buoyancy to the initial metacenter and can be expressed as:

$$BM = I_T / \nabla \tag{9.3}$$

Where IT – moment of inertia of the water-plane area about the transverse axis of the waterline; ∇ – submerged volume of the hull. For a rectangular water-plane area, the moment of inertia can be found by the formula:

$$I_T = LB^3 / 12 \tag{9.4}$$

Where L – length of the water-plane; B – beam of the water-plane.

KB is the distance from keel to center of buoyancy. An approximate value of KB is found from Morrish's Formula, which states:

$$\text{Depth of center of buoyancy below waterline} = \frac{1}{3}\left(\frac{d}{2} + \frac{\nabla}{A_w}\right) \tag{9.5}$$

Where d – draft; ∇ – submerged volume of the hull; AW – area of water-plane.

This equation gives us the following:

$$KB = d - \frac{1}{3}\left(\frac{d}{2} + \frac{\nabla}{A_w}\right) \tag{9.6}$$

KG is the distance from keel to the center of gravity, i.e. the vertical center of gravity (VCG) of the ship, and this measure depends on the distribution of weights. The lightship weight and VCG are measured when the ship is new. The final KG is found by taking the moments of all the weights with respect to the keel.

$$KG = \frac{Final\ moment}{Final\ displacement} \tag{9.7}$$

The formula for longitudinal stability:

$$GM_L = KB + BM_L - KG \tag{9.8}$$

Where,

$$BM_L = \frac{I_L}{\nabla} \quad (9.9)$$

$$I_L = BL^3/12 \quad (9.10)$$

Here BM_L – longitudinal metacentric radius; I_L – longitudinal moment of inertia, other words, moment of inertia of the water-plane area about the transverse axis of the water-plane; ∇ – submerged volume of the hull; L – length of the water-plane; B – beam of the water-plane.

The ship is stable (initial stability), when GM is positive. If the ship is inclined to a small heel angle, the vertical center of gravity remains the same and the vertical center of buoyancy (VCB) is changed. This condition creates a moment to return the ship upright.

$$\text{Moment of statical stability} = W * GZ \quad (9.11)$$

Where W – displacement and GZ – righting arm.

For small angles of heel (up to 7˚) we can assume that the initial metacenter remains the same, and we can use the following simplified equation [23]:

$$GZ = GM * sin\theta \quad (9.12)$$

This shows that righting moments will vary with initial GM.

If GM > 0 ⇒ the moment of statical stability > 0 and we have initial stability.

If GM = 0 ⇒ the moment of statical stability = 0 and we have indifferent condition. It means, that vessel will not go back to the initial position, when the inclination moment is taken away.

If GM < 0 ⇒ the moment of statical stability < 0 and the condition is unstable. The vessel will continue to incline, even if the inclination moment is taken away [16].

GZ is taken as the perpendicular distance between the vertical center of gravity and the vertical line through the vertical center of buoyancy. See **Figure 9.2**.

9.2.2. Initial stability analysis

As in was said before, the metacentric height is the primary term regarding vessel's initial stability.

Initial stability will be calculated for the case of maximum load and draft. Parameters for initial stability calculations are given below [29]:

Height, H = 4.4 m;

Draft, d = 2.9 m;

Displacement, W = 2093 tons.

According to the equation 9.1 and Russian Maritime Register of Shipping requirements:

Freeboard=H–d=4.4–2.9=1.5 m > 0.005L = 0.005∗65.1 = 0.3255 m

KB and BM can be found according to the equations 9.3 and 9.6. For further calculations these parameters were taken from the hydrostatics table (**Table 9.1**), retrieved from Free!Ship Software (discussed in the Chapter 9.3):

$$KM = KB + BM = 10.637 \text{ m} \tag{9.13}$$

Corresponding to the equation 9.2 and the minimum approved value of the KM with regards to the Russian Maritime Register of Shipping requirements, the maximum value of KG is:

$KG_{\max} = KB + BM - GM_{\min} = 10.637 - 0.15 = 10.487$ m

Ship will not be stable, if KG will be more, than 10.487 m. It should be taken into consideration during vessel deck layout designing and ship loading.

9.3. Free!Ship analysis

"Free!Ship" is a free computer program used for vessel hulls design. The software has a variety of pre-designed hulls, which are available for downloading. It provides hydrostatics calculations and cross curves of stability analysis.

Hydrostatics parameters can be found from the **Table 9.1**.

A stability curve is a curve, which is drawn for each heel angle and for the whole interval of possible displacements. These curves are plotted against the displacement value on the horizontal axis and a KN value on the vertical axis. There is a different plot for each angle of inclination. As the KG of the ship varies for different loading scenarios the cross curves are normally plotted for a KG value of zero referred to as KN. The correction for the KG value is made when the actual KG is known.

The GZ values can be read from the cross curves (see **Figure 9.3**). To obtain the GZ for a known displacement, locate the displacement on the horizontal axis on the cross curve, draw a perpendicular line to this displacement and this line will cut through curves for all intervals of heeling angles. From the intersection with these curves draw a horizontal line and read of the uncorrected GZ values on the vertical axis. After the correction for the KG value is made the corrected GZ value can be plotted against heeling angles on the horizontal axis, and GZ value on the vertical axis. The curve is then known as a GZ curve. The GZ curves are drawn for different displacements and KG [34].

Useful information, which can be deducted from the GZ curve:

- It can be assumed, that the slope of the curve at the origin represents the value of GM for small heel angles.
- The angle at which GZ becomes zero is known as the point of vanishing stability and defines the range of stability.
- The area under the curve up to any given angle, multiplied by the displacement, represents the energy needed to heel the ship to that angle.

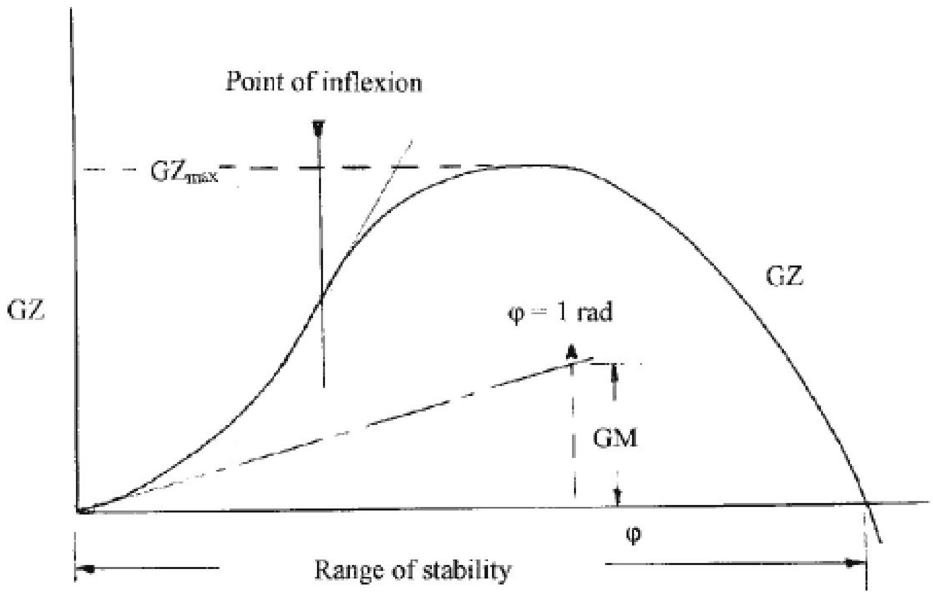

Figure 9.3 – GZ cross curve.

The hull designed in this program is based on the default model of the tug, which was modified to suit the design of the Arcticaborg. The lines plan of the designed Arcticaborg's hull is presented on the **Figure 9.4**. The work place of the Free!Ship is shown on the **Figure 9.5**. This model is based on the available and free information and is not 100% accurate.

Table 9.1 – Hydrostatics calculation results.

Draft	Lwl	Bwl	Volume	Displ.	LCB	VCB	Cb	Am	Cm	Aw	Cw	LCF	Cp	S	KMt	KMl
m	m	m	m^3	tonnes	m	m	[-]	m^2	[-]	m^2	[-]	m	[-]	m^2	m	m
2.300	57.631	15.771	1442.2	1478.3	31.138	1.350	0.6899	31.685	0.8735	836.26	0.9201	29.135	0.7898	954.17	12.488	141.24
2.400	57.989	15.803	1526.3	1564.4	31.024	1.405	0.6940	33.262	0.8770	844.89	0.9220	29.016	0.7913	971.98	12.096	137.09
2.500	58.373	15.835	1611.2	1651.5	30.916	1.460	0.6972	34.848	0.8803	853.37	0.9232	28.902	0.7920	989.76	11.743	133.30
2.600	58.758	15.868	1696.9	1739.4	30.811	1.515	0.7000	36.424	0.8829	861.76	0.9243	28.792	0.7929	1007.5	11.424	129.84
2.700	59.146	15.900	1783.5	1828.1	30.711	1.570	0.7024	38.009	0.8854	870.08	0.9252	28.685	0.7934	1025.4	11.135	126.68
2.800	59.545	15.933	1870.9	1917.7	30.613	1.625	0.7043	39.604	0.8877	878.41	0.9259	28.578	0.7934	1043.3	10.874	123.81
2.900	59.970	15.966	1959.2	2008.2	30.519	1.681	0.7056	41.212	0.8901	886.80	0.9262	28.470	0.7927	1061.4	10.637	121.22

Legend:

Lwl: Length on waterline	Cm: Midship coefficient
Bwl: Beam on waterline	Aw: Waterplane area
Volume: Displaced volume	Cw: Waterplane coefficient
Displ.: Displacement	LCF: Waterplane center of floatation
LCB: Longitudinal center of buoyancy, measured from the aft perpendicular at X=0.0	Cp: Prismatic coefficient
VCB: Vertical center of buoyancy, measured from the lowest point of the hull	S: Wetted surface area
Cb: Block coefficient	KMt: Vertical transverse metacenter
Am: Midship section area	KMl: Longitudinal transverse metacenter

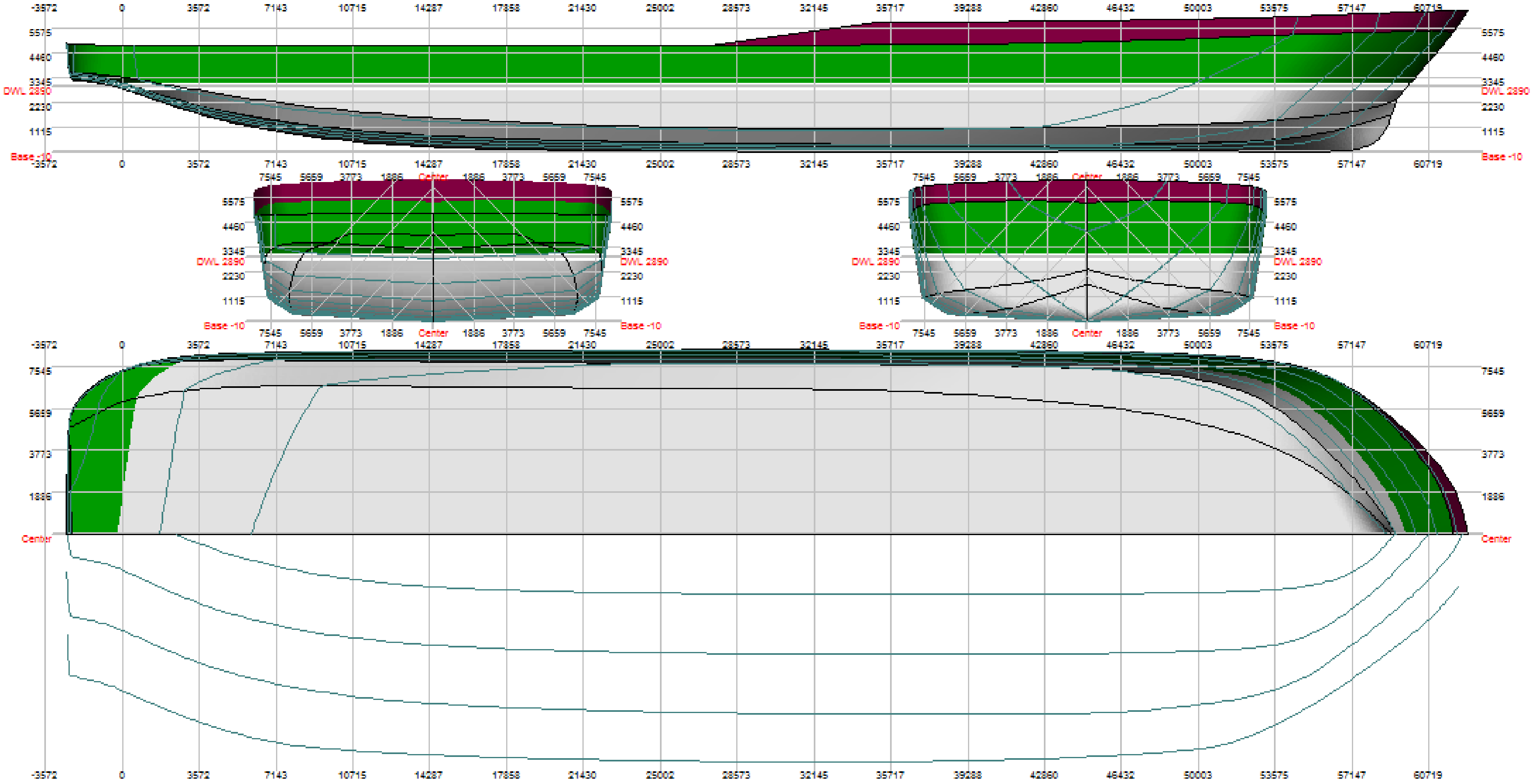

Figure 9.4 – Lines plan of the Arcticaborg model, “Free!Ship” software.

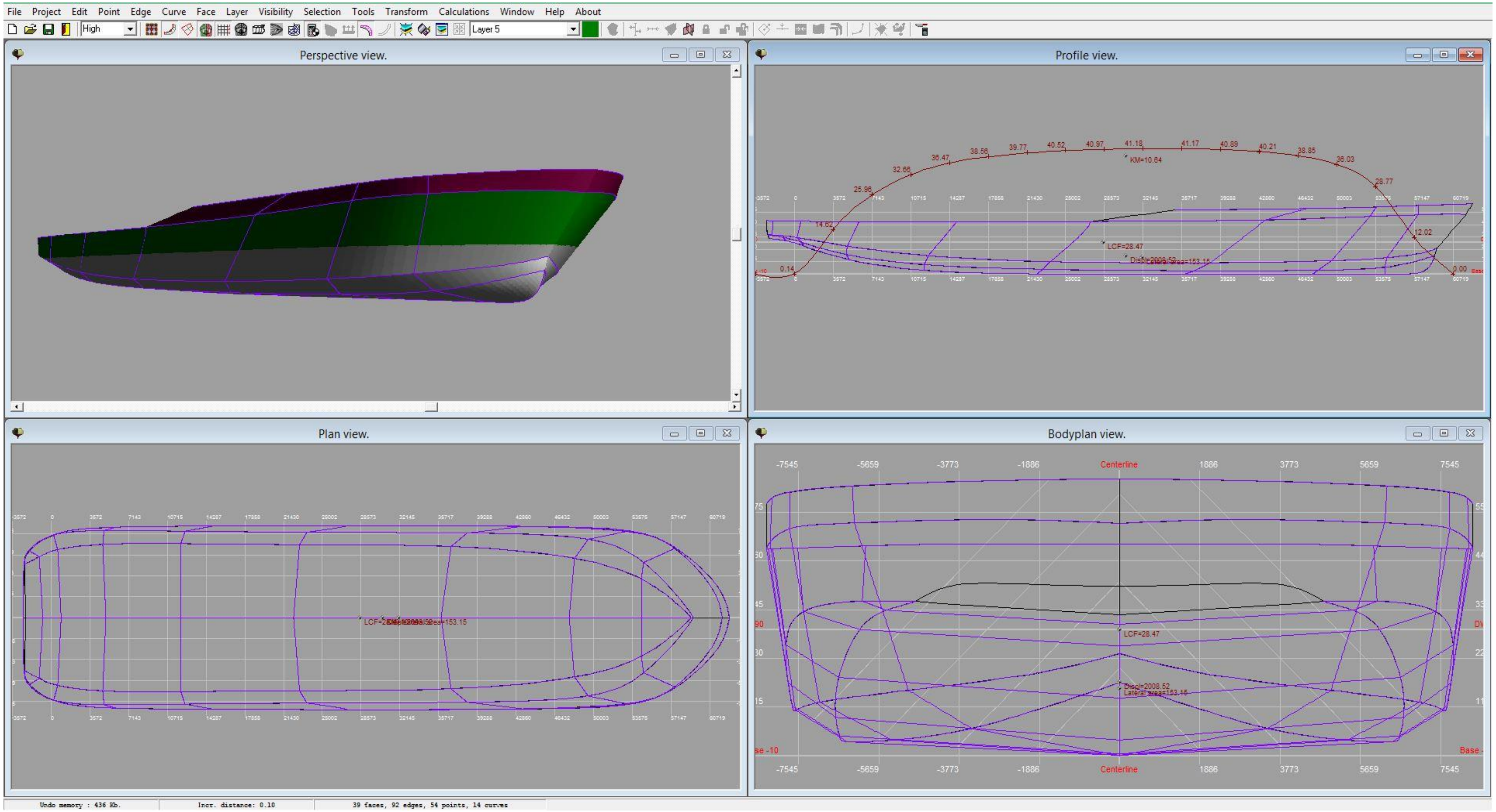

Figure 9.5 – Workspace, Free!Ship software.

Cross curves of stability are presented on the **Figure 9.6**. From the plot, we can obtain, that the operation interval of heel angles for the Arcticaborg is up to 18 degrees, which depends on the loading condition. Plot is based on the calculations for a wide interval of displacements (1000–3000 tonnes); red dotted line means the real interval of the vessel's displacement. Minimum loading condition corresponds to 2.3 m draft and maximum to 2.9 m.

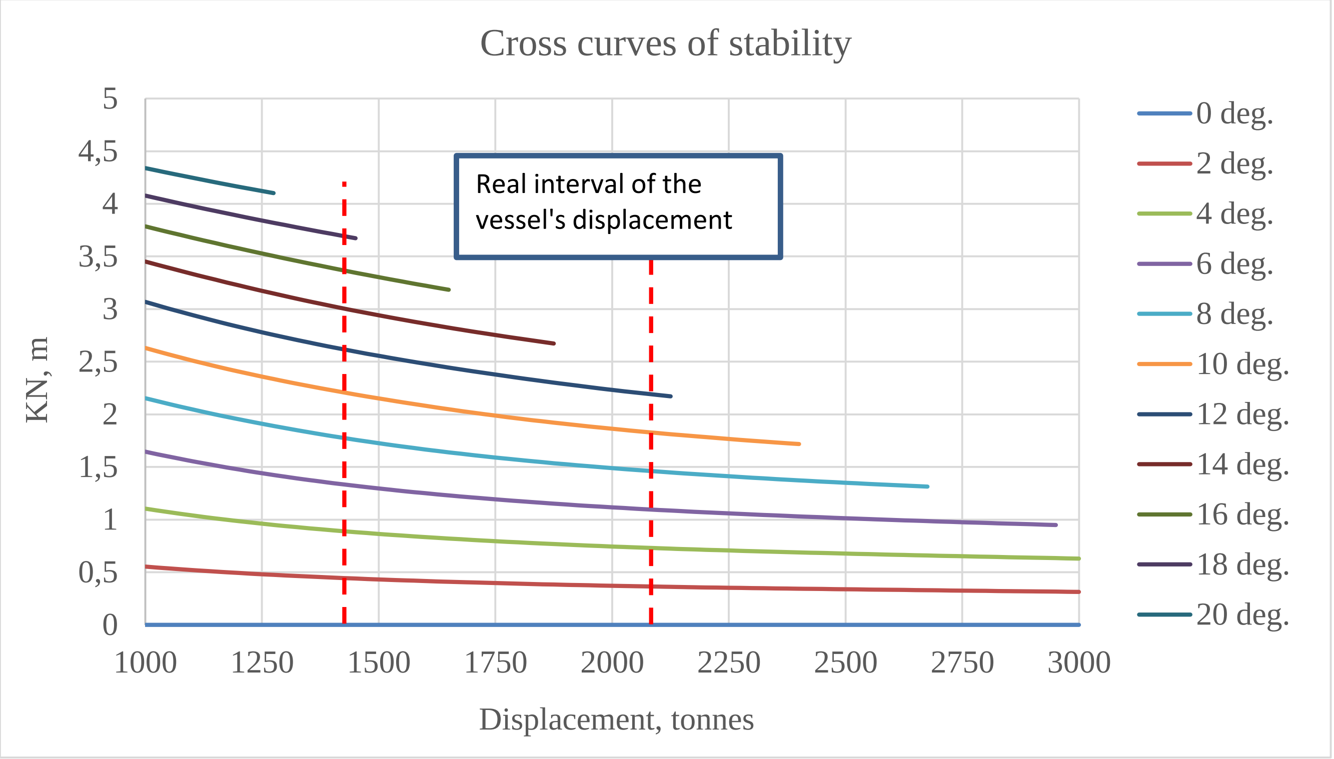

Figure 9.6 – Cross curves of stability.

Chapter 10. Sea ice aspects

10.1. Ice actions

Sea ice is a complex crystalline material mainly consisting of pure ice, brine and gas (air). Its properties are determined by the molecular structure, temperature, salinity, density and different impurities that take place within it. Moreover, sea ice properties significantly vary from one region to another.

The ice actions determine the ice failure modes, character of the influence of ice on offshore structures and, therefore, it is of interest to discuss them in this project (see **Figure 10.1**). Since this report relates to the Northern part of the Caspian Sea, only aspects of sea ice, which are relevant for this region, are presented. It should be noted that only first-year ice takes place in the Caspian Sea, so multi-year ice is not discussed.

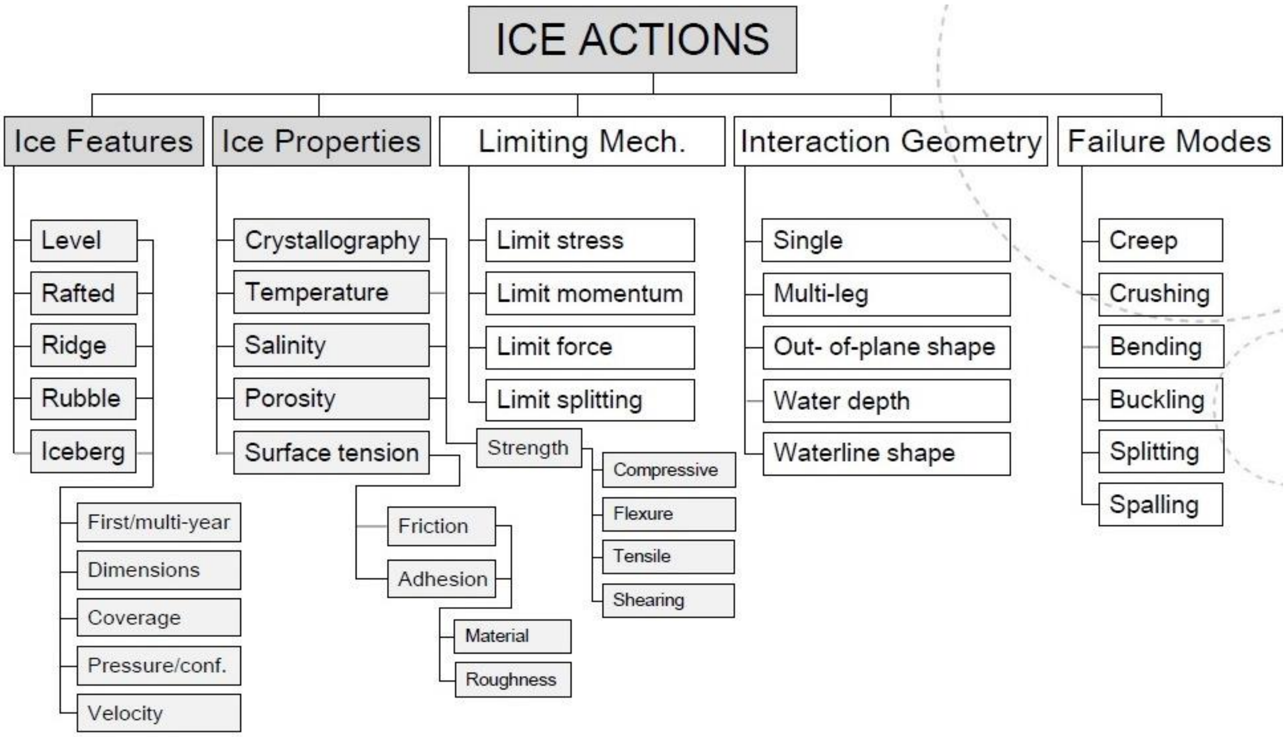

Figure 10.1 – Ice actions

Source: [24].

10.1.1. Mechanical properties

Sea ice is an inhomogeneous, anisotropic and nonlinear viscous material [32]. Ice mechanical properties include tensile, compressive, flexural, shear strengths coupled with Young modulus, Poisson ratio and friction coefficients are functions of the physical properties (the structure of ice, brine volume, porosity), temperature, the confinement of the ice sample, strain rate, etc [25].

The following section describes the mechanical properties that are important for the Northern Caspian Sea.

Compressive strength

Compressive strength is the maximal principal stress corresponding to failure begging under ice compression [26]. Generally, ice preferably fails in compression taking place when thick ice interacts with offshore structures [41].

Ice is featured by two kinds of inelastic behaviors under compression (see **Figure 10.2**). On basis of the shape of the stress-strain curve, several zones can be determined: (I) brittle regime, (II) ductile regime and (III) transition zone.

Ice exhibits ductile behavior when the stress-strain curve has a plateau and, on the other hand, the strain rate is lower than $\varepsilon_{D/B}$. The peak stress (or ductile compressive strength) increases with (I) increasing strain rate; (II) with decreasing temperature and (III) with decreasing salinity and porosity of the ice.

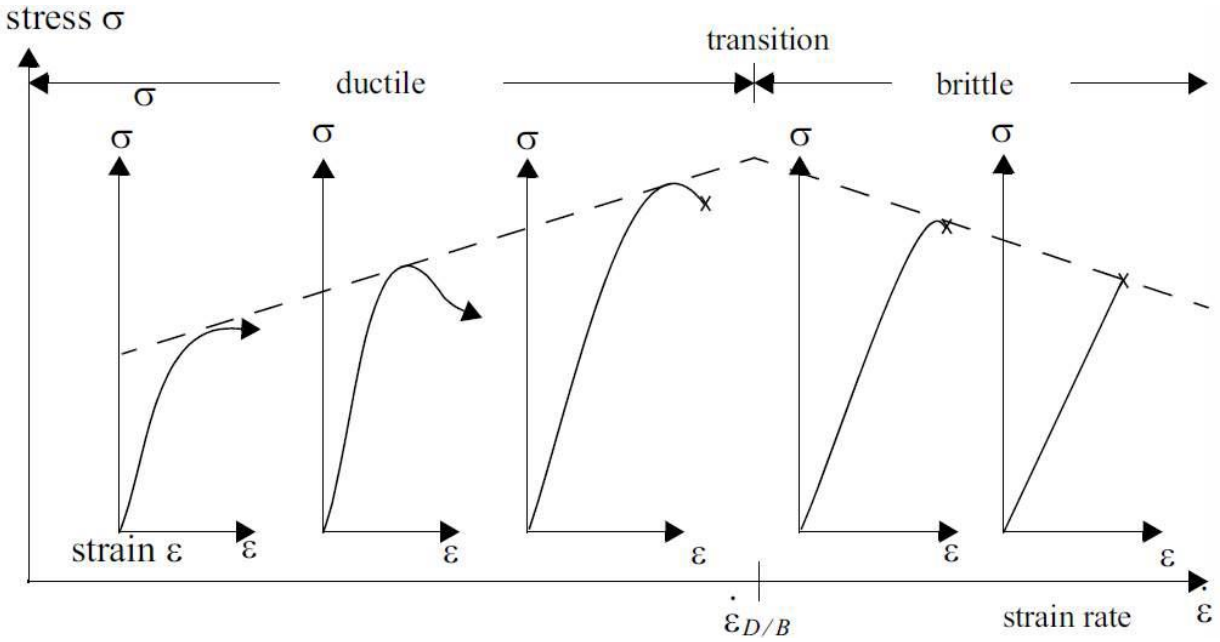

Figure 10.2 – Scheme showing the effect of strain rate on the compressive stress-strain behavior of ice.

Source: [32].

Tensile strength

Tensile strength is the maximal principal stress corresponding to failure begging under ice tension [26]. Note that the tensile strength in vertical loading is three times higher than for horizontal one due to the ice structure and the ice growth direction. In addition, compressive and tensile strengths might vary significantly along different directions, but the compressive strength is normally 2-4 times larger than its tensile strength.

Typical values for first-year ice range from 0.13 MPa to 0.67 MPa (most of the Caspian measurements were carried out for the coastal zone). This is also close to the tensile strength of freshwater ice ranging from 0.7 to 3.1 MPa [28].

Flexural strength

Flexural strength is the ability of a brittle material to resist deformation under flexural loading conditions. In contrast to the compressive strength, the flexural strength of sea ice has not strict correlations with the loading rate. Since this parameter characterizes the material bearing capacity, the flexural strength is an important parameter for calculations of the ice action on sloping actions.

Typical values of flexural strength of sea ice measured in the Caspian Sea do not exceed 2.17 MPa while most of the results are in the range 0.41—1.20 MPa (see **Figure 10.3**). However, the mean flexural strength based on 553 measurements in the North Caspian Sea is 0.78 MPa [40].

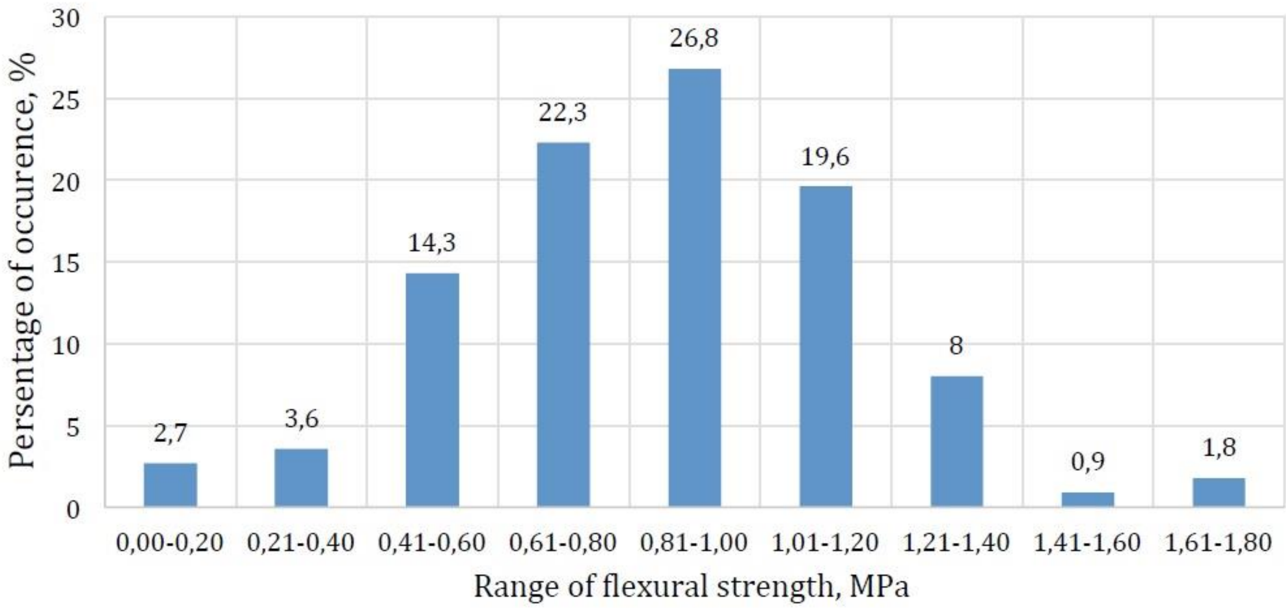

Figure 10.3 – Flexural strength of ice in the Northern Caspian Sea based on 112 measurements.

Source: [40].

<u>Shear strength</u>

“In engineering practice, the shear strength is not usually explicitly used. Since ice tends to fracture rather than to flow in a crack-free, volume-conserving manner, the shear strength is actually governed by the tensile strength of the ice. Since most ice engineering issues occur at higher loading rates (i.e. when ice exhibits brittle behavior – the author’s note), the compressive strength is much higher than the tensile strength. Thus, ice loaded with a shear condition would fail in tension rather than in shear” [41].

However, the shear strength is an important material property to consider because the interaction between ice and structures is subjected to a biaxial stress state involving tensile stresses in addition to the compressive or shear stress. The author could found no reported measurements of the shear strength of the Caspian Sea ice, so the values of shear strength of columnar sea ice ranged from 550kPa to 900 kPa are proposed for the further discussion [15].

<u>Young's modulus and Poisson's ratio</u>

Elastic properties of ice are featured by an elasticity modulus and Poisson ratio.

Elasticity modulus, often called Young's modulus, is defined as the ratio of the stress to the strain during elastic deformations (according to the Hook's law). One can notice that the total strain ε_{ij}^{total} is defined as a sum of the following strain components (the strains' tensors (i j) are used because sea ice is considered as an anisotropic material):

$$\varepsilon_{ij}^{total} = \varepsilon_{ij}^{elastic} + \varepsilon_{ij}^{delayed} + \varepsilon_{ij}^{vscous} + \varepsilon_{ij}^{cracking}$$

where $\varepsilon_{ij}^{elastic}$ is the instantaneous elastic strain tensor; $\varepsilon_{ij}^{delayed}$ is the delayed elastic strain; $\varepsilon_{ij}^{vscous}$ is the viscous or permanent strain and $\varepsilon_{ij}^{cracking}$ is the cracking (tertiary) strain.

Note that in continuum mechanics of ice, it is not correct to call the elastic modulus as Young's modulus because any mechanical measurements involve the elastic and the viscoelastic components in this equation, while the elastic modulus relates only to the elastic behavior of ice. However, in this project the term Young's modulus is used.

The typical values of Young's modulus of ice in the Caspian Sea do not exceed 2.5 – 3.5 $\times 10^9$ MPa and this is three times lower than for river ice.

Poisson's ratio is defined as the ratio of the lateral strain to the longitudinal strain in a homogeneous material for a uniaxial loading condition. It should be noted that measured values of the ratio would be more correct to call the Effective Poisson's ratio because the elastic response is mainly involved instead of purely viscoelasticity effects. Despite that there is no available data related to reported measurements of Poisson ratio in the Caspian Sea, its value is suggested 0.33 [41].

10.1.2. Ice features

In this section, only the ice features that are relevant for the Northern Caspian Sea are presented [44]:

- Level ice is considered as sea ice that has not been subjected to deformation and has relatively uniform thickness.
- Rafted ice is defined as an ice feature formed when separate ice fields interact with each other. Due to currents and winds these ice fields override each other without a large amount of rubbles formation and eventually they adfreeze together.
- Ridges are formed when thick ice sheets interact with each other causing deformation of their edges and generate significant ice rubbles at the contact area.
- Stamukhas are grounded ridges that are usually formed in shallow water where interaction between fast ice and drifting ice exists.

10.2. Resistance of ships in unbroken level ice

Retrieved from Professor Sveinung Løset lectures for AT-327 "Arctic Offshore Engineering" course (UNIS, autumn semester 2016) [24].

A number of efforts are made to estimate the performance of ships in ice. They are mostly based on empirical relations either acquired from ships transiting in ice (full-scale data) or model-scale tests performed in ice basins. In the following, I will make a short review and end up with what people believe is the most suitable algorithms for the present study.

The resistance of a ship advancing in unbroken ice depends mainly on

- Hull dimensions and geometric form;
- Ice thickness;
- Ice strength;

- Dynamic friction ice-hull;
- Speed of ship.

Other factors are snow cover on the ice, its temperature and wetness.

This model is based data acquired from a number of sea trials with ships (Keinonen; 1991, 1996) covering a range of ship sizes and bow forms as well as ice conditions [20]. It takes into account:

- Ship size;
- Bow form;
- Type of propulsion;
- Friction;
- Snow conditions;
- Ice conditions.

The prediction equation for resistance (units MN) in unbroken level ice, normalized to a speed of 1 m/s, has the following form.

$$\begin{aligned} R_{ice} &= 0.015 HC \cdot S && (10.1) \\ &\times B^{0.7} L^{0.2} D^{0.1} h^{1.5} && \leftarrow \textit{ship size term} \\ &\times (1 - 0.0083(T + 30)) && \leftarrow \textit{friction term} \\ &\times (0.63 + 0.00074\sigma_f) && \leftarrow \textit{ice strength term} \\ &\times (1 + 0.0018(90 - \gamma)^{1.6}(1 + 0.003(\beta - 5)^{1.5}) && \leftarrow \textit{bow form term} \end{aligned}$$

where

HC – hull condition factor;

S – factor for salinity of water;

B – ship beam (m);

L – ship waterline length;

D – draft (m);

h – equivalent ice thickness;

$h = h_i + h_s$ (m), where h_i (m) and h_s (m) is ice and snow thickness;

T – ice surface temperature (°C);

σ_f - flexural strength of ice (kPa);

γ – average bow flare angle at waterline (°);

β – average buttock flare angle at waterline (°);

The ship size terms are displayed on **Figure 10.4**.

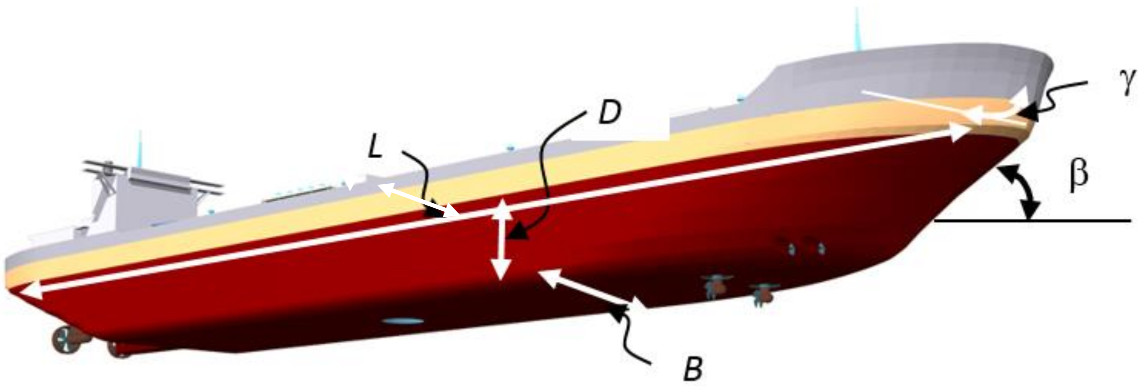

Figure 10.4 – Characteristic ship hull parameters.

Source: [24].

Keinonen et al. (1996) [20] have also modified Eq. (1) to include the influence of speed. The additional resistance at speeds greater than 1 m/s is given by the following relation (units in MN):

$$R_{ice}(V > 1\,m/s) = 0.009HC\,(\Delta V/(gL)^{0.5}) \quad (10.2)$$

$$\times B^{1.5}D^{0.5}h_i \quad \leftarrow \textit{ship size term}$$

$$\times(1-0.0083(T+30)) \quad \leftarrow \textit{friction term}$$

$$\times(1+0.0018(90-\gamma)^{1.6}(1+0.003(\beta-5)^{1.5}) \quad \leftarrow \textit{bow form term}$$

Where

$\Delta V = V - 1$ (units m/s);

g = 9.81 m/s.

Note that the velocity dependent component of resistance is linear in both V and hi.

The open water resistance (MN) is given by

$$R_{ow} = (Displ)^{1.1}(0.025F_n + 8.8F_n^5)/1000 \quad (10.3)$$

Where

$$Displ = \rho_w LBDC_b \text{ (tons)};$$

ρ_w - density of sea water;

Cb – block coefficient;

$F_n = V / \sqrt{gL}$ (Froude number).

The total resistance is given by the sum of Eq. (10.1-3).

$$R = R_{ice} + R_{ice}(V > 1\, m/s) + R_{ow} \quad (10.4)$$

Open water thrust at maximum power absorbed (units MN) is

$$T_{ow} = 0.75 P_s (0.122 - 0.0057V) \quad (10.5)$$

where P_s is shaft power (units MW). Note that for an open fixed pitch propeller only 75 % of shaft power is absorbed at maximum speed.

Running in ice is an overload situation and the maximum thrust is given by

$$T_{max} = P_s(1 - 0.25V/V_{\max})(0.111 - V(0.0057V_{\max} - 0.011)/V_{\max}) \quad (10.6)$$

10.3. Ice resistance calculations

The Ice breaking support/supply vessel Arcticaborg was taken as a reference point for the calculations. This ship is now operating on the Kashagan field in the Kazakhstan's sector of the Caspian Sea, where ice and wave conditions are almost the same, as on the Filanovsky field. This vessel is Ice Class 1A Super according to Finnish-Swedish classification (see Chapter 7.3). Parameters of the vessel used in calculations are given in the **Table 10.1** [29].

Table 10.1 – Arcticaborg and ice parameters for calculations.

Hull condition factor	dimensionless	HC	1.33
Ship beam	m	B	16.4
Ship waterline length	m	L	57.68
Ship total length	m	L total	65.1
Draft	m	D	2.9

Displacement	ton	Displ	2093
Waterline average bow flare angle	deg	γ	75
Waterline average buttock flare angle	deg	β	35
Cruising speed in the ice	m/s	V_i	1.5
Cruising speed in open water	m/s	V_{ow}	6.5
Propulsion power	MW	P	3.24
Average ice surface temperature	deg C	T	-10
Flexural strength	kPa	σ_f	800
Salinity of water	ppt	S	9.5
Seawater density	t/m^3	ρ	1010.5
Ice thickness	m	h_i	0.9

1) The prediction equation for resistance (units MN) in unbroken level ice, normalized to a speed of 1 m/s, has the following form as reported by Frederking (2003).

$$\begin{aligned} R_{ice} &= 0.015HC \cdot S \\ &\times B^{0.7}L^{0.2}D^{0.1}h^{1.5} && \leftarrow \textit{ship size term} \\ &\times(1-0.0083(T+30)) && \leftarrow \textit{friction term} \\ &\times(0.63+0.00074\sigma_f) && \leftarrow \textit{ice strength term} \\ &\times(1+0.0018(90-\gamma)^{1.6}(1+0.003(\beta-5)^{1.5}) && \leftarrow \textit{bow form term} \end{aligned}$$

R_{ice}=1.6425 MN

2) The additional resistance at speeds greater than 1 m/s is given by the following relation (units in MN):

$$\begin{aligned} R_{ice}(V>1\,m/s) &= 0.009HC\,(\Delta V/(gL)^{0.5}) \\ &\times B^{1.5}D^{0.5}h_i && \leftarrow \textit{ship size term} \\ &\times(1-0.0083(T+30)) && \leftarrow \textit{friction term} \\ &\times(1+0.0018(90-\gamma)^{1.6}(1+0.003(\beta-5)^{1.5}) && \leftarrow \textit{bow form term} \end{aligned}$$

R_{ice_1}=0.0234 MN

3) The open water resistance (MN) is given by

$$R_{ow} = (Displ)^{1.1}(0.025F_n + 8.8F_n^5)/1000$$

R_{ow}=0.1034 MN

4) The total resistance is given by

$$R = R_{ice} + R_{ice}(V>1\,m/s) + R_{ow}$$

R_{total}=1.7693 MN

5) Open water thrust at maximum power absorbed (units MN) is

$$T_{ow} = 0.75 P_s (0.122 - 0.0057V)$$

T_{ow}=0.2038 MN

6) Running in ice is an overload situation and the maximum thrust is given by

$$T_{max} = P_s (1 - 0.25V / V_{\max})(0.111 - V(0.0057V_{\max} - 0.011) / V_{\max})$$

T_{max}=0.3227 MN

We have obtained that the power of the vessel in open water exceeds the resistance movement of the ship. Power of the vessel in ice conditions (0.9 m ice thickness) is less than the total resistance, for this reason we need an additional support – the icebreaker. Hence, we need to use icebreakers operating nowadays in the Northern Caspian Sea, such as Kapitan Chechkin (see **Figure 10.5**).

Figure 10.5 – Kapitan Chechkin.

Source: [68].

7) According to the calculations, made in the MATLAB software, the maximum ice thickness of level ice for Arcticaborg for independent sailing is 0.3 m. Parameters for this ice thickness are as following:

R_{ice}=0.2122 MN

R_{ice_1}=0.0060 MN

R_{ow}=0.1034 MN

R_{total}=0.3216 MN

T_{ow}=0.2038 MN

T_{max}=0.3227 MN

Due to the results, we can see that the power of vessel is enough for moving independently in 0.3 m thickness of unbroken level ice.

Chapter 11. Optimum equipment selection and deck equipment layout

The first step in planning of the vessel deck equipment layout is to constitute a list of the required equipment based on the expected job scope. The analysis must determine the largest expected single treatment and largest well or maximum number of treatments that the vessel must complete without reloading materials from shore. In addition to class and regulatory compliance, example considerations for vessel layout include [7]:

- Sufficient space between equipment for routine maintenance and repair work;
- Clear areas for walkways, escape routes, additional storage, and HSE equipment (fire extinguishers, safety showers, secondary containment, etc.);
- Sea fastenings for deck equipment as per class and regulatory requirements;
- Deck strength analysis in cases where point loads potentially exceed the area of deck-loading limits;
- Stability simulations according to local weather expectations and class standards.

During broad analysis of the layout configurations, several types of the existing modular systems were studied:

1. FlexStim Modular Offshore Stimulation System, Schlumberger [14];
2. Vessel-based Modular Solution – VMS, Halliburton [43];
3. StimFORCE Modular Stimulation System, Baker Hughes [38].

All suppliers provide complete flexible stimulation equipment packages, that can cover a variety of operations, such as gravel pack, fracturing, acidization and others. Nevertheless, these solutions are not suitable for Northern Caspian Sea conditions. All of them require 700-1000 m^2 of free deck area. This parameter corresponds to ships with rather high draft, typically more than 5.5 m. As it was mentioned before, these vessels are unable to get to the Caspian Sea through The

Unified Deep Water System of European Russia. In addition, these vessels cannot get to ports, due to the maximum depth 5 m.

Solution for this problem can serve as an individually designed deck equipment layout.

First step was to choose the form of the equipment. After brief consideration was chosen a mobile hydraulic fracturing, coiled-tubing and acidizing fleet with both frame and containerized versions. This form is also modular and means that there are several predesigned layouts for every offshore stimulation operation. These modules can be quickly replaced at the port and vessel with new layout will be ready for new operation execution. The only owner and supplier of this equipment in Russia is LLC “Packer Service”. All types of the equipment can operate in low winter temperatures of the Northern Caspian Sea.

11.1. Considered equipment

1. Frame high-pressure pump (Figure 11.1), [8].

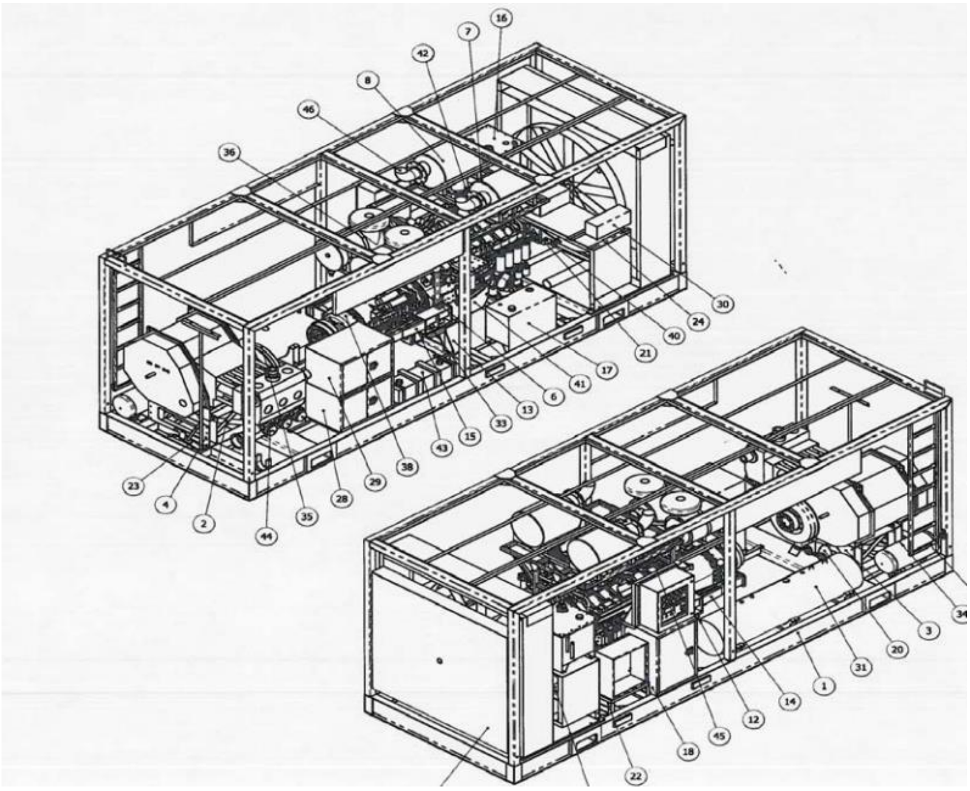

Figure 11.1 – Frame high-pressure pump.

This high-pressure fracturing pump may be used for a wide variety of fluid pumping operations. Typical operations include proppant hydraulic fracturing, acid fracturing, high-pressure pumping, solvent pumping, liquid carbon dioxide pumping and pressure testing. The components integrated into this model are arranged to provide reasonable access for maintenance and simplicity of operation. The unit is designed accordingly to the latest safety requirements and maintains operator safety as a primary objective. The deck engine to run the pumping package is a MTU Diesel engine rated to 1,680 kW (2,253 BHP – Brake horsepower). The Unit can be remotely operated either from a remote control module or from the data van through a Mobile Computerized Data Acquisition and Control Unit.

This unit is designed and built for severe temperatures ranging from - 30°C to +40°C and is suitable for the Northern Caspian Sea conditions. One 1000-liter capacity fuel tank is installed on the Skid frame. The Skid is equipped with reinforced slots in the low beam to handle it with a crane or helicopter. If the Unit will be too heavy it is easily to remove the triplex pump. All fluid connections to the triplex pump are quick connections. To start the pump engine two hydraulic starters are mounted which will be powered from external hydraulic supply via quick connectors. Parameters and possible variants of the triplex pump are presented on the **Figure 11.2**.

The approximate physical dimensions of this unit are as follows:

- Length – 8500 mm;
- Width – 2450 mm;
- Height – 3000 mm;
- Weight – 26000 kg.

Load on the deck is approximately 1.25 t/m^2, which is less than the maximum value of 5 t/m^2.

PLUNGER DIAMETER	OUTPUT PER REV	DISPLACEMENT AT PUMP STROKES PER MINUTE / PINION RPM											
		75 / 476		115 / 731		148 / 943		200 / 1271		300 / 1906		330 / 2096	
in (mm)	gal/rev (liter/rev)	gpm (lpm)	psi (kg/cm²)	gpm (lpm)	psi (kg/cm²)	gpm (lpm)	psi (kg/cm²)	gpm (lpm)	psi (kg/cm²)	gpm (lpm)	psi (kg/cm²)	gpm (lpm)	psi (kg/cm²)
3½ (88.9)	1.00 (3.8)	75 (284)	24,796 (1747)	115 (435)	24,796 (1747)	148 (562)	23,390 (1648)	200 (757)	17,361 (1223)	300 (1135)	11,574 (816)	330 (1249)	10,522 (742)
3¾ (95.3)	1.15 (4.3)	86 (326)	21,600 (1522)	132 (499)	21,600 (1522)	170 (645)	20,375 (1436)	229 (869)	15,124 (1066)	344 (1303)	10,082 (711)	379 (1433)	9,166 (646)
4 (101.6)	1.31 (4.9)	98 (371)	18,985 (1338)	150 (568)	18,985 (1338)	194 (734)	17,908 (1262)	261 (988)	13,292 (937)	392 (1483)	8,861 (624)	431 (1631)	8,056 (568)
4½ (114.3)	1.65 (6.3)	124 (469)	15,000 (1057)	190 (719)	15,000 (1057)	245 (928)	14,150 (997)	330 (1251)	10,502 (740)	496 (1876)	7,002 (493)	545 (2064)	6,365 (449)
5 (127.0)	2.04 (7.7)	153 (579)	12,150 (856)	235 (888)	12,150 (856)	303 (1146)	11,461 (808)	408 (1544)	8,507 (600)	612 (2316)	5,671 (400)	673 (2548)	5,156 (363)
5½ (139.7)	2.47 (9.3)	185 (701)	10,042 (708)	284 (1074)	10,042 (708)	366 (1387)	9,472 (668)	494 (1869)	7,031 (495)	741 (2803)	4,687 (330)	815 (3083)	4,261 (300)
5¾ (146.1)	2.70 (10.2)	202 (766)	9,187 (647)	310 (1174)	9,187 (647)	401 (1516)	8,666 (611)	540 (2042)	6,433 (453)	809 (3063)	4,288 (302)	890 (3370)	3,898 (275)
6 (152.4)	2.94 (11.1)	220 (834)	8,438 (595)	338 (1279)	8,438 (595)	436 (1651)	7,959 (561)	588 (2224)	5,908 (416)	881 (3336)	3,938 (278)	969 (3669)	3,580 (252)
6½ (165.1)	3.45 (13.0)	259 (979)	7,190 (507)	396 (1501)	7,190 (507)	512 (1937)	6,782 (478)	690 (2610)	5,034 (355)	1,034 (3915)	3,356 (236)	1,138 (4306)	3,051 (215)
6¾ (171.5)	3.72 (14.1)	279 (1055)	6,667 (470)	428 (1618)	6,667 (470)	552 (2089)	6,289 (443)	744 (2814)	4,668 (329)	1,115 (4222)	3,112 (219)	1,227 (4644)	2,829 (199)
7 (177.8)	4.00 (15.1)	300 (1135)	6,199 (437)	460 (1740)	6,199 (437)	594 (2247)	5,848 (412)	800 (3027)	4,340 (306)	1,200 (4540)	2,894 (204)	1,319 (4994)	2,630 (185)
7½ (190.5)	4.59 (17.4)	344 (1303)	5,400 (381)	528 (1998)	5,400 (381)	681 (2579)	5,094 (359)	918 (3475)	3,781 (266)	1,377 (5212)	2,521 (178)	1,515 (5733)	2,291 (161)
INPUT POWER: BHP (Kw)		1205 (899)		1848 (1379)		2250 (1679)		2250 (1679)		2250 (1679)		2250 (1679)	

Figure 11.2 – Possible triplex pump solutions.

2. <u>Installation for data collection, monitoring and management of CAT GmbH in containerized variant, [8].</u>

The C.A.T. Data Van is a container mounted, model F-DACU-T-6, mobile computerized data acquisition and control unit, obligatory for pre-designing of fracturing jobs, data analysis, and control of the fracturing operation.

It is equipped with all required and user friendly software and hardware, industrial-grade computers, displays, printer, pumper control panel, which may be used for data obtaining, running of fracturing programs, etc.

This unit is provided with a supplementary frac control center for onboard job design and cost frac analysis. This unit will be capable of running the existing frac spreads.

Technical Data:

- Connection for external power supply;
- Separate control room and spectator compartment;

- Intercom system for operators;
- Air condition system;
- Process monitors in spectator compartment;
- Remote control for all frac operations;
- Computer with frac design program;
- Recorder for all frac parameters.

All frac parameters are input into the operating software before the treatment. All functions are operated completely automatically. Any function can be changed at any time either in the data van or in the blender.

The container is air-conditioned, completely insulated and suitable for operating in harsh arctic conditions of oil and gas fields. This container is equipped with two doors according to the safety requirements. Plan and view of the container are presented on the **Figures 11.3** and **11.4** respectively.

The right part of the container is equipped with the following components:

- Fridge, Freezer;
- Chemical laboratory for analysis of frac chemicals;
- Projector for real time view of the process data;
- Seating area.

The left part of the container is equipped with the following components:

- 2 Computers with UPS;
- 6 Control panels for pumper units;
- Blender Automatic Control Panel;
- Meyer Data Acquisition and Design Software.

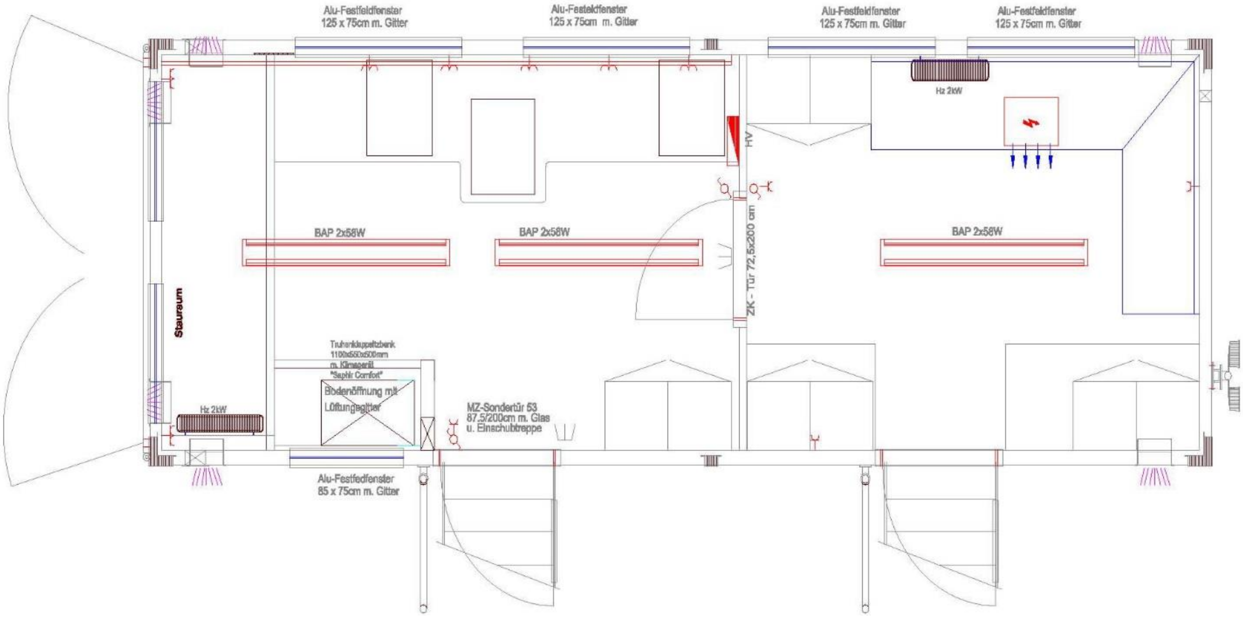

Figure 11.3 – Plan view of the data van.

Figure 11.4 – Data van appearance.

The approximate physical dimensions of this unit are as follows:

- Length – 8400 mm;
- Width – 2500 mm;
- Height – 2591 mm;
- Total weight – ~10.500 kg.

Load on the deck is approximately 0.5 t/m^2, which is less than the maximum value of 5 t/m^2.

3. Installation of automated feeding chemicals for hydraulic fracturing CAT GmbH model F-ACU-T-5, containerized type, [8].

The insulated chemical container consists of two different sections:

Front section. There is a laboratory in the front section of the container where chemicals can be tested in site. An operator panel can be additionally installed. All working processes such as pumping, mixing, dosing, are controlled automatically or manually by tools of the operator panel.

Rear section. Six electrical driven dosing pumps are installed in the middle part of the container. A flow meter can be additionally installed behind each dosing pump. Following pumps are used:

- 2 x progressive cavity pump 0,5 -25 L;
- 2 x progressive cavity pump 1 - 40 L;
- 2 x progressive cavity pump 2 - 120 L;

The rear part of the container is used for transport of chemicals tanks. There are four stainless steel tanks, one with the capacity of approximately 2 m^3 without agitators, two tanks with the capacity of 3 m^3 each including one agitator and one guar tank with a capacity of 5 m^3 including two agitators.

The Unit is equipped with an additional centrifugal pump and a Magnetic inductive (MID) flow meter to mix fluids in storage tanks.

The container is equipped with an internal heating system (electrical). This heating system provides a constant temperature of 20° C inside. The heating system prevents freezing of pumps and pipes.

All installed pumps work independently. Along with the flow meter, the pumps provide an exact dosing of chemicals as well as a constant-controllable mass flow. Due to an automatic monitoring system of chemicals, this unit ensures the maximum safety during oilfield operations.

The approximate physical dimensions of this unit are as follows:

- Length – 12000 mm;
- Width – 2550 mm;
- Height – 4000 mm;
- Total dry Weight – ~26.800 kg.

Load on the deck is approximately 0.88 t/m^2, which is less than the maximum value of 5 t/m^2.

4. Coiled tubing unit (CTU)/Hose reel unit with high and low pressure manifold system installed.

The CTU commonly consists of actuating system mechanism (injector head, drum, and guider), power system and control system (hydraulic, electric and pneumatic control system).

The drum is one of the most important parts of the coiled tubing unit, mainly consists of drum body, pipe racking system, drive system, counting system, manifold system, lubricating system, etc. (see **Figure 11.5**) and directly decides the transport dimension of the CTU and its coiled tubing winding capacity [5].

The high-pressure hose hanger, drum and hoses/tubing can be easily designed and manufactured locally by engineering firms and manufacturing shops. Although, other parts of the CTU are commonly purchased as a bundled unit from qualified suppliers to ensure the equipment quality [7]. Type of the using tubing depends on well parameters and pressure required for successful operation.

CTU covers a plenty of operations and can be also used for well maintenance, fishing operations, logging, side-tracking in drilling, etc [27]. All of the above equipment can be simply installed in the skid frame and used on the vessel's deck.

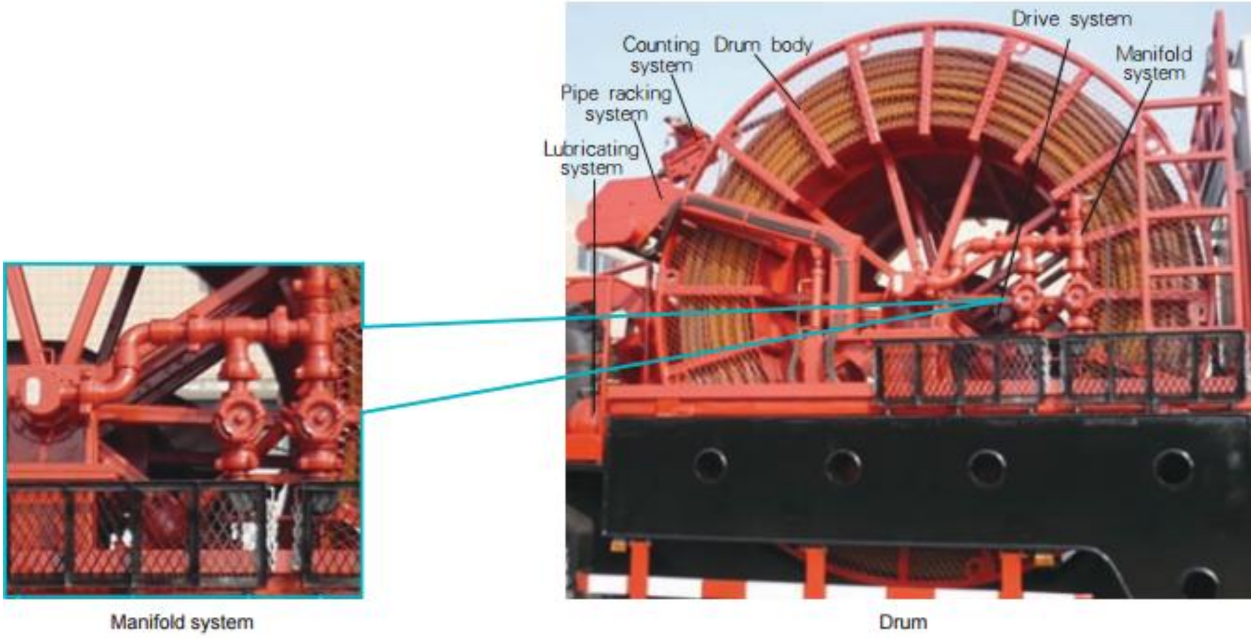

Figure 11.5 – CTU drum and its components.

5. <u>Proppant tanks/bunkers.</u>

Arcticaborg is manufactured with bulk tanks, which volume is 51 m^3. These tanks can be used for proppant or other bulk materials used in well intensification operations. In case of lack of the volume, additional tanks can be used.

In this paper, tanks manufactured by Sibneftemash Company are considered (available from: http://www.sibneftemash.ru/en) [54]. Tanks are operated in vertical position, transport position is horizontal. Tanks can be set into operating or transport positions using both crane and special machines with the help of self-lifting mechanism (see **Figure 11.6**). Admitted minimum working temperature is -40 ^{0}C.

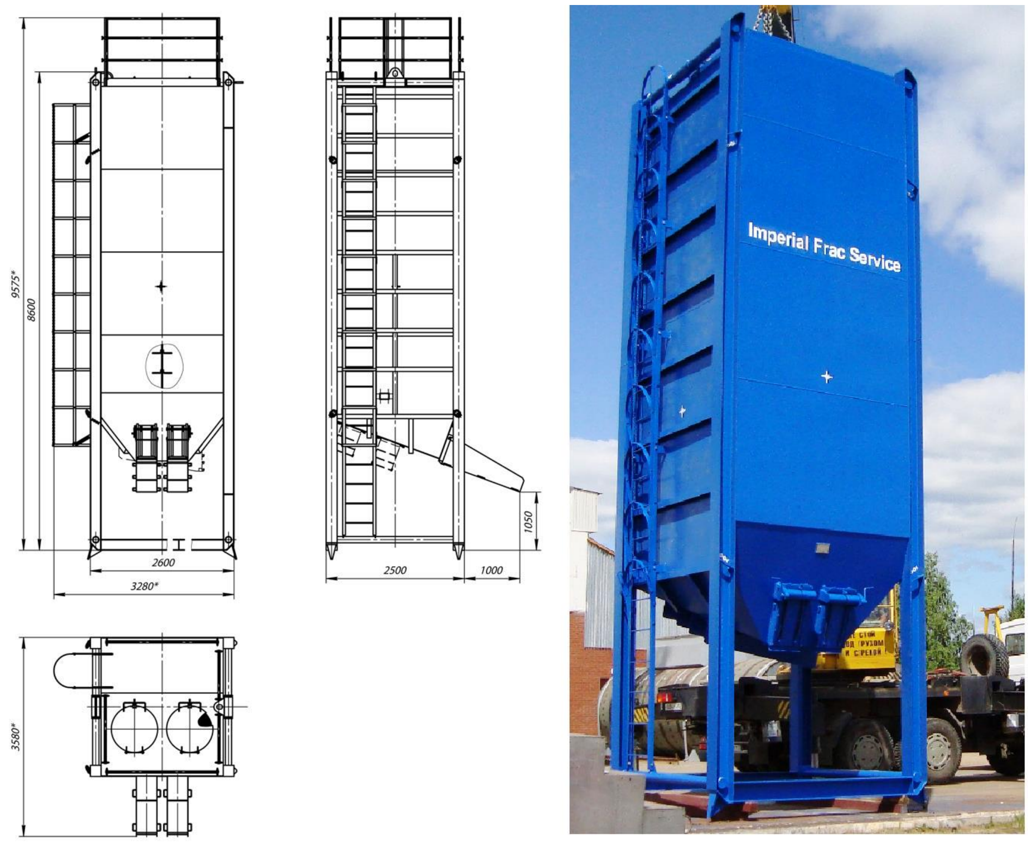

Figure 11.6 – Vertical proppant tank.

Supplier provides different variants of bunkers:

- With volume capacity 28 m^3;
- With volume capacity 33 m^3;
- With volume capacity 40 m^3.

Sizes are for transport position, thus in operating position length is height, and height is length (see **Figure 11.7**). Two-section variant is also available. It has two main benefits: helps to mitigate free surface effect and allows using proppant of two different fractions.

Parameter	Value					
Version	PB-28	2PB-28	PB-33	2PB-33	PB-40	2PB-40
Number of sections	1	2	1	2	1	2
Tank capacity, m^3	28	28	33	33	40	40
Gate valve actuator (drive)	manual					
Sizes/dimensions, mm, less than: Length Width (taking ladder hoop railing into account) Height	7 770 2 500 2 690		8 770 2 500 2 690		8 665 3 650 3 300	9 000 3 150 3 300
Weight, kg less than	5 650	7 650	6 650	7 800	10 060	10 050

Figure 11.7 – Vertical proppant tanks specifications.

Typical values of proppant density are:

- Super light proppant – lower than 2 t/m^3 up to 1.01 t/m^3;
- Sand – 2.65 t/m^3;
- Ceramic proppant – 2.7-3.3 t/m^3;
- Supertough proppant – 3.2-3.8 t/m^3.

51 m^3 volume of the default Arcticaborg tank can handle more than 150 tons of ceramic proppant (density = 3 t/m^3). This volume is sufficient for standard hydraulic fracturing of similar to Filanovsky oil field reservoirs (e.g. established operation on Rakushechnoe field, which was discussed in the Chapter 6.1. Fracturing brigade pumped 50 tons of proppant into the well). Supertough proppant is not needed for reservoirs with pressure 17 MPa. It is common to use sand, ceramic or light proppant for such conditions. However, in case of necessity of additional tanks, crew should be very careful with deck load limit.

Other concern is stability. High center of gravity of these tanks will change COG of the whole system and, consequently, GM. All cases should be properly calculated during design stage in order to avoid capsizing.

Light proppant can be used with reservoir pressure up to 10000 psi (68 MPa) [69]. This is enough for conditions of the Filanovsky cluster of fields. The deck load for each tank and for each proppant density is shown on the **Table 11.1** (red color means exceedence of the deck load limit).

Table 11.1 – Maximum deck load for each tank depending on the proppant density.

Proppant density, t/m3	PB-28	2PB-28	PB-33	2PB-33	PB-40	2PB-40
1,0	5,00	5,30	5,90	6,07	4,16	4,81
1,1	5,42	5,72	6,39	6,56	4,49	5,20
1,2	5,84	6,13	6,88	7,05	4,82	5,58
1,3	6,25	6,55	7,37	7,54	5,15	5,97
1,4	6,67	6,97	7,86	8,03	5,48	6,35
1,5	7,09	7,38	8,35	8,52	5,82	6,74
1,6	7,50	7,80	8,84	9,01	6,15	7,12
1,7	7,92	8,22	9,33	9,50	6,48	7,51
1,8	8,33	8,63	9,82	9,99	6,81	7,89
1,9	8,75	9,05	10,31	10,48	7,14	8,28
2,0	9,17	9,46	10,80	10,97	7,48	8,66
2,1	9,58	9,88	11,29	11,46	7,81	9,05
2,2	10,00	10,30	11,78	11,96	8,14	9,43
2,3	10,42	10,71	12,28	12,45	8,47	9,82
2,4	10,83	11,13	12,77	12,94	8,81	10,20
2,5	11,25	11,55	13,26	13,43	9,14	10,59
2,6	11,67	11,96	13,75	13,92	9,47	10,97
2,7	12,08	12,38	14,24	14,41	9,80	11,36
2,8	12,50	12,80	14,73	14,90	10,13	11,74
2,9	12,91	13,21	15,22	15,39	10,47	12,13
3,0	13,33	13,63	15,71	15,88	10,80	12,51

Table 11.2 shows how much proppant of each density we can fill in the particular tank in order not to exceed maximum deck load limit.

Table 11.2 – Maximum proppant volume for each tank.

Proppant density, t/m3	PB-28	2PB-28	PB-33	2PB-33	PB-40	2PB-40
1,0	28,0	26,0	27,0	25,8	40,0	40,0
1,1	25,4	23,6	24,5	23,5	40,0	38,1
1,2	23,3	21,7	22,5	21,5	40,0	34,9
1,3	21,5	20,0	20,8	19,9	38,6	32,3
1,4	20,0	18,6	19,3	18,5	35,8	30,0
1,5	18,7	17,3	18,0	17,2	33,4	28,0
1,6	17,5	16,2	16,9	16,1	31,4	26,2
1,7	16,5	15,3	15,9	15,2	29,5	24,7
1,8	15,5	14,4	15,0	14,4	27,9	23,3
1,9	14,7	13,7	14,2	13,6	26,4	22,1
2,0	14,0	13,0	13,5	12,9	25,1	21,0
2,1	13,3	12,4	12,9	12,3	23,9	20,0
2,2	12,7	11,8	12,3	11,7	22,8	19,1
2,3	12,2	11,3	11,7	11,2	21,8	18,2
2,4	11,7	10,8	11,2	10,8	20,9	17,5
2,5	11,2	10,4	10,8	10,3	20,1	16,8
2,6	10,8	10,0	10,4	9,9	19,3	16,1
2,7	10,4	9,6	10,0	9,6	18,6	15,5
2,8	10,0	9,3	9,6	9,2	17,9	15,0
2,9	9,7	9,0	9,3	8,9	17,3	14,5
3,0	9,3	8,7	9,0	8,6	16,7	14,0

Free surface effect can occur, if tanks are not fully filled, but much smaller in comparison with liquids. Obtaining these results, we can make a conclusion that the most suitable solution is to use light covered proppant with pour density 1-1.2 t/m^3.

I want to note once again, that 51 m^3 volume of the default bulk tank is sufficient for most of the kinds of fracturing operations. Furthermore, there is no concern about proppant density and high COG in this tank.

6. <u>Gel tanks.</u>

Arcticaborg is manufactured with liquid mud tanks, which volume is 48 m^3. These tanks can be also used for fracturing gel and other chemicals. In case of lack of the volume, additional tanks can be used.

Sibneftemash Company produces two types of gel tanks: vertical and horizontal [54].

Vertical gel tank.

This type of tanks has the same problems as a vertical proppant tank, such as stability and deck load concern. The only appropriate solution in order not to exceed the deck load limit is to use VGE-50 tank with volume 50 m^3 (supplier provides four options). Density of the fracturing gel is typically 1-1.1 t/m^3.

Parameters of the tank are as following:

- Length – 3750 mm;
- Width – 3250 mm;
- Height – 8140 mm;
- Dry mass of the tank – 7000 kg;
- Admitted minimum working temperature is -40 ^{0}C.

Thus, load on the deck is approximately 5 t/m^2, which is equal to the maximum value of 5 t/m^2.

Horizontal gel tank.

A distinctive feature of this horizontal gel tank is that its body is manufactured as a completed transport-mounting unit with top clamps and a bracket for mounting of the hook grab of the self-lifting system.

Benefits of this tank in comparison with vertical tanks are:

- Less load on 1 m^2 of the deck;
- Less influence on COG and stability.

Disadvantages are:

- More concern about free surface effect;
- Requires more space on the deck.

Figure 11.8 – Horizontal gel tank.

Parameters of the tank are as following:

- Volume – 50 m^3;
- Length – 9500 mm;
- Width – 3000 mm;
- Height – 2863 mm;
- Dry mass of the tank – 6200 kg;
- Admitted minimum working temperature is -45 ^{0}C.

Load on the deck (full tank) is approximately 2.15 t/m^2, which is less than the maximum value of 5 t/m^2.

7. Blender.

Blender is the "heart" of hydraulic fracturing fleet. It is the main element of the process. Blender is designed for fracturing fluids preparation and mixing them with proppant. High viscosity liquids can carry greater concentrations of proppant to the wellbore.

Blender installed on the skid frame should be used on the deck. For instance, Axon Company provides this solution (data is available from http://axonep.com/frac-pac-blender-units) [70].

I want to pay more attention on the new blender technology – Blender Unit with Integrated Container Support Frame [35]. This is an up-to-date equipment patented on 26 January 2017 by Halliburton Energy Services, Inc [55].

This technology and equipment is focused on managing of bulk material efficiently. The support frame is used to carry several portable containers of bulk material/proppant, and the blender unit includes a gravity feed outlet for getting proppant from the containers directly into a mixer of the blender (see **Figure 11.7**).

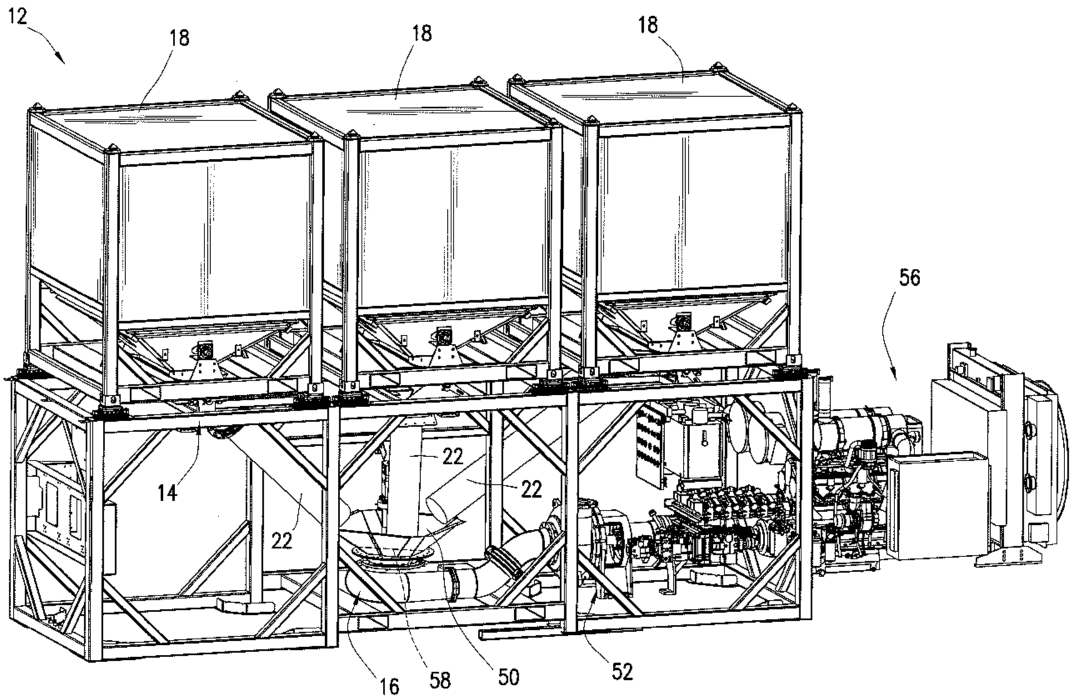

Figure 11.9 – Blender Unit with Integrated Container Support Frame. Source: [35].

Detailed description can be found in the Patent (available in references).

Main concerns are:

- To stay within maximum deck load limit;
- Stability of a vessel;
- New technology without any practical experience.

This integrated blender has several very important benefits in the lack of space and weight limitation conditions:

- Eliminates the need for any subsequent mechanical conveyance of the bulk material from containers to a mixer;
- This unit may be lighter weight;
- Requires less space;
- Has a lower cost and complexity in comparison with the existing blenders.

11.2. Deck equipment layouts

The studied equipment is combined into several layouts depending on purpose (**Figures 11.10 – 11.13**). One gray box corresponds to 1 m^2, dimensions of all parts are shown on the pictures. Four variants are:

1. Deck equipment layout for hydraulic fracturing with one horizontal frac tank (**Figure 11.10**).

This is the simplest solution. Two pumps are used. Default 51 m^3 bulk tank is enough for proppant; one additional horizontal tank is used for gel storage.

2. Deck equipment layout for hydraulic fracturing with two horizontal frac tanks and additional deck (**Figure 11.11**).

In case of necessity of the additional frac tank, second proposed combination can be used. Additional deck should be constructed on the top of gel tanks, and Data van should be mounted there.

Total load on the deck is about 3 t/m^2 including weight of the steel additional deck which is less than the maximum value of 5 t/m^2.

3. Deck equipment layout for hydraulic fracturing with three vertical frac tank or proppant tank areas (**Figure 11.12**).

If we need more storage for gel or proppant, 3^{rd} solution should be used. It is planned to use three vertical tanks. Restricted area for vertical tanks on the plan corresponds to maximum dimensions of the possible tanks discussed previously.

4. Deck equipment layout for well acidizing (**Figure 11.13**).

This arrangement is used for traditional low pressure acidizing. Only one pump is used for this type of operation. 90.75 m^2 of free space is left and can be used for additional tools, tanks and equipment.

Maximum total weight of the equipment with full additional (three tanks for 4^{th} deck equipment layout) and default tanks (bulk and liquid mud tanks) is approximately 572 tons (520 tons + 10% as a reserve), which is less than the maximum deadweight equal 650 tons. For all layouts, the minimum distance between equipment is 0.7 m due to safety regulations and to simplify the maintenance works.

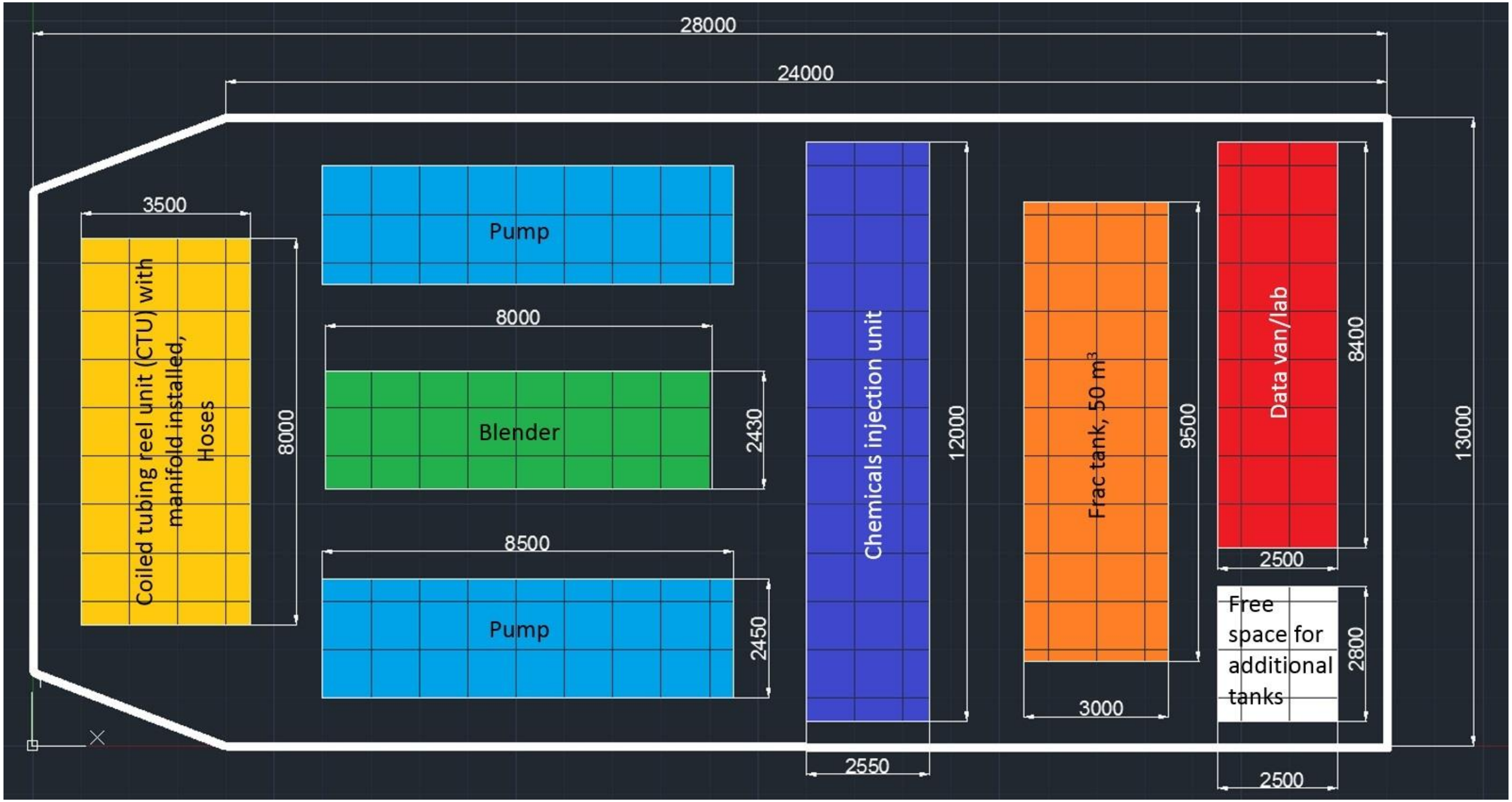

Figure 11.10 – Deck equipment layout for hydraulic fracturing with one horizontal frac tank.

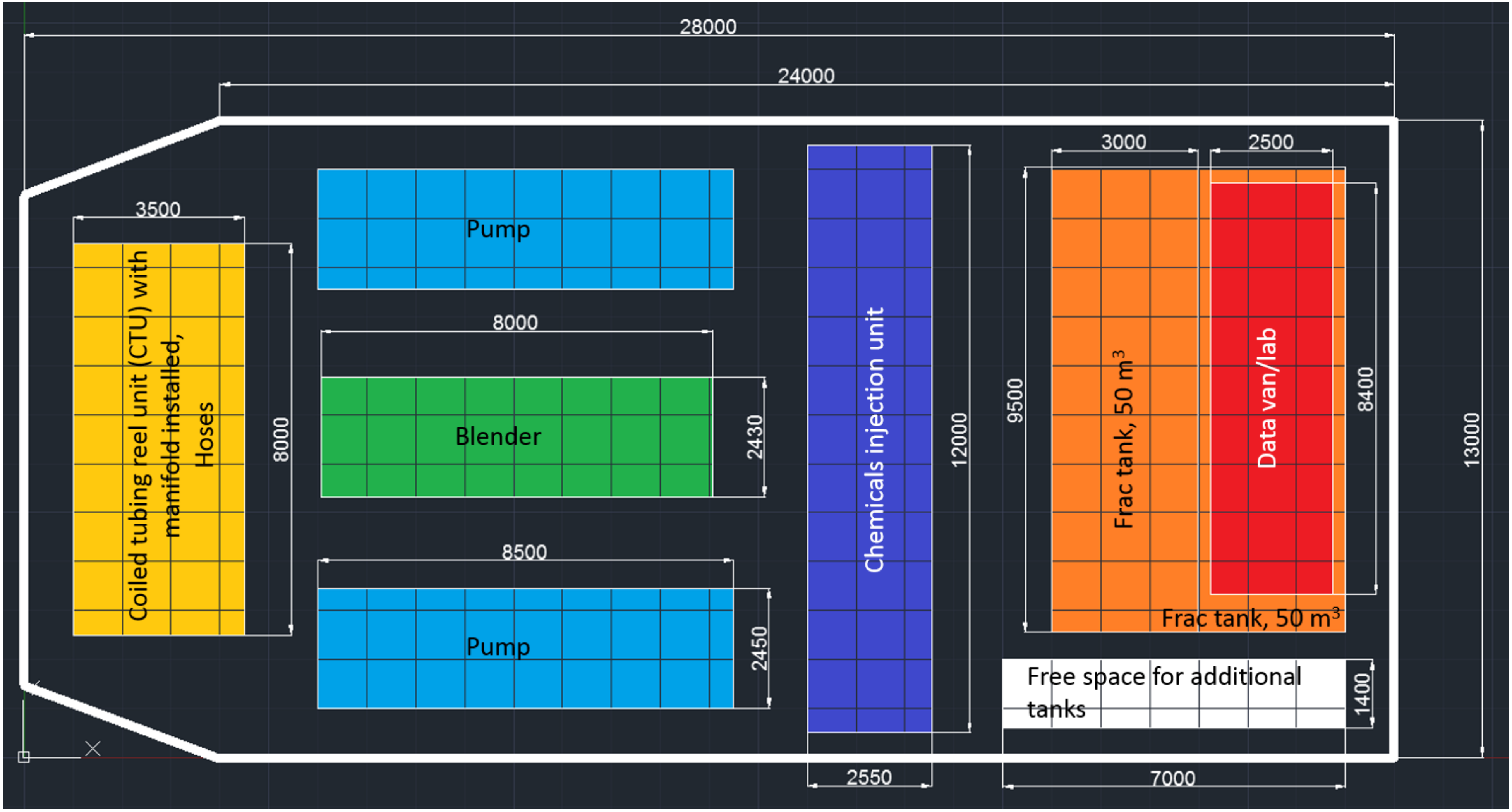

Figure 11.11 – Deck equipment layout for hydraulic fracturing with two horizontal frac tanks and additional deck.

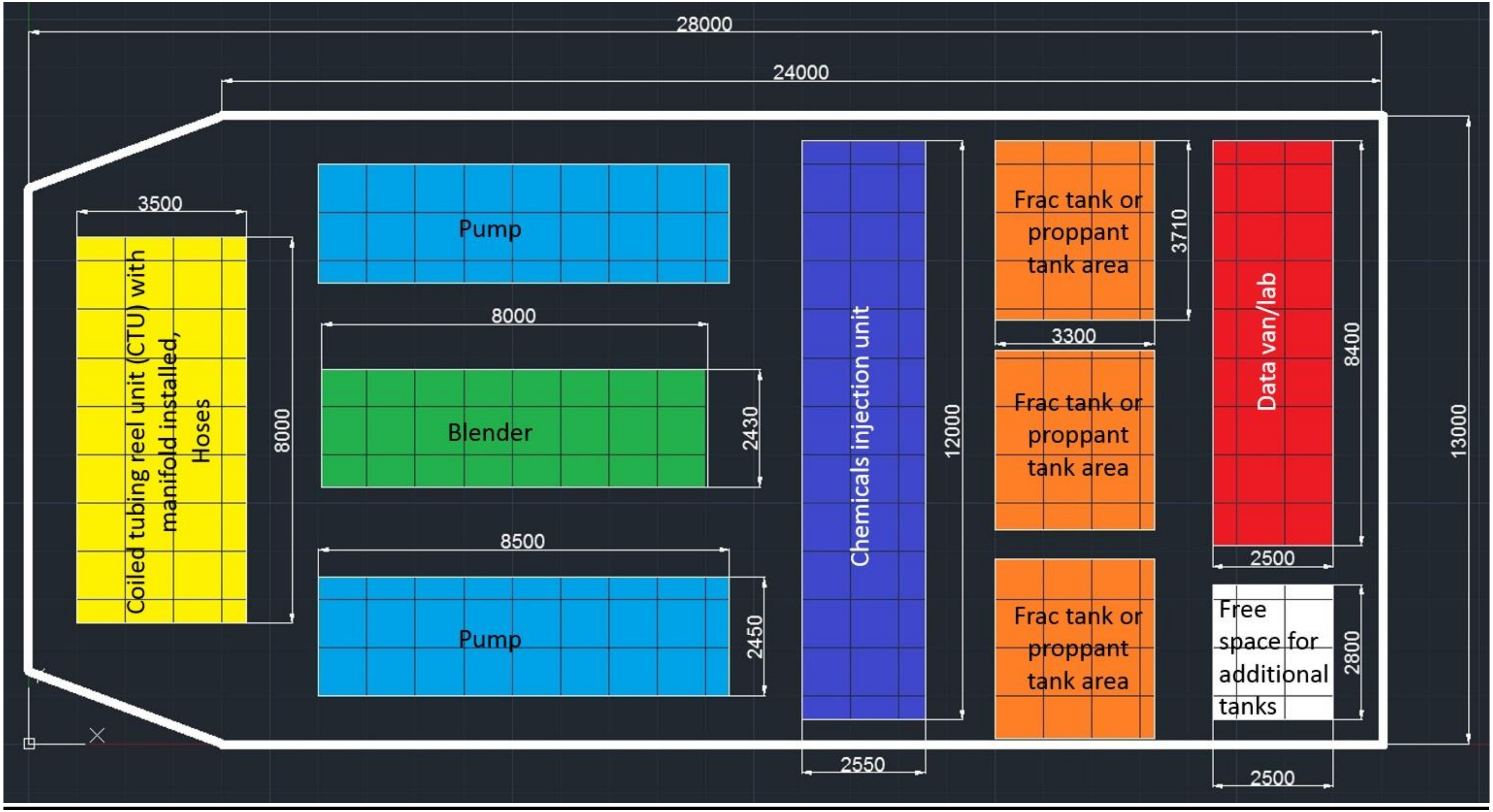

Figure 11.12 – Deck equipment layout for hydraulic fracturing with three vertical frac tank or proppant tank areas.

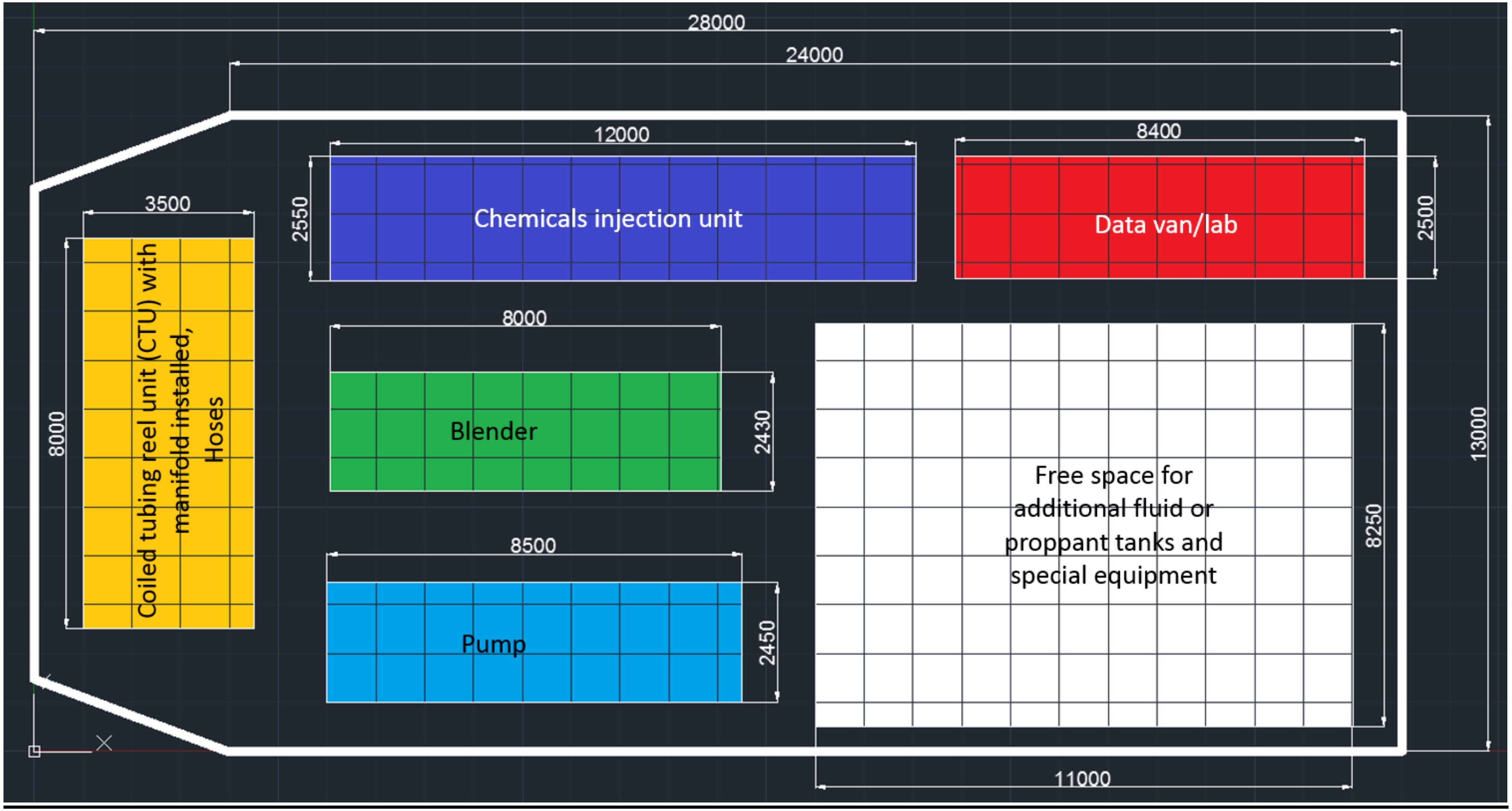

Figure 11.13 – Deck equipment layout for well acidizing.

Chapter 12. Health, safety and environment regulations (HSE)

Health, Safety and Environment (HSE) is an umbrella term for the laws, rules, guidance and processes designed to help protect employees, the public and the environment from harm. HSE management has two general objectives: prevention of incidents or accidents that might result from abnormal operating conditions and reduction of adverse effects that result from normal operating conditions [37].

In Russia HSE are regulated by the State Standards or GOSTs (ГОСТ in Russian), which should be approved by the Federal Service for Ecological, Technological and Nuclear Supervision – Rostekhnadzor. The structure of Russian normative base in the field of oil and gas industrial safety is provided on **Figure 12.1** [6].

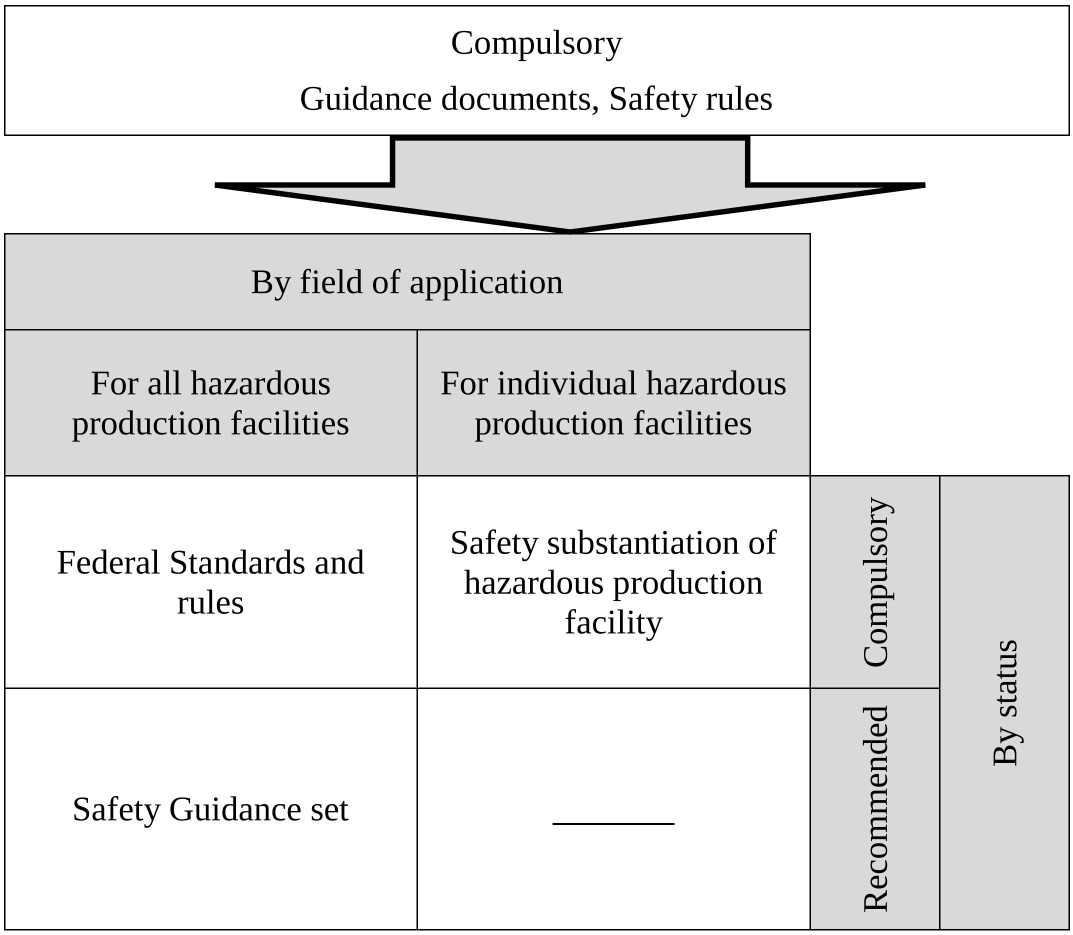

Figure 12.1 – The structure of Russian normative base in the field of oil and gas industrial safety.

Source: [6].

These standards should be considered in the development of the conceptual design of a vessel and technology discussed in the thesis. I took into account the following State Standards:

1. Federal norms and rules for the HSE “The Safety rules in oil and gas industry” with amendments, approved by the Decree of Rostekhnadzor, January 12, 2015 № 1 (valid since January 1, 2017). In Russian: Федеральные нормы и правила в области промышленной безопасности "Правила безопасности в нефтяной и газовой промышленности" (с изменениями на 12 января 2015 года).

Some main points for hydraulic fracturing:

- Hydraulic fracturing is carried out under the supervision of the responsible engineering and technical worker according to the work plan approved by the technical manager of the organization.
- It is prohibited for the personnel to be near the wellhead and at the injection pipelines during the hydraulic fracturing.
- The pressure header of the manifold block must be equipped with sensors, safety valves and a liquid discharge line. Discharge pipelines should be equipped with backpressure valves. The piping scheme before the hydraulic fracturing should be coordinated with the blow-out prevention service.
- After wellhead setup, it is necessary to do a pressure test of the injection pipelines with a safety factor of at least 1.25.
- During the acid hydraulic fracturing (acid frac), corrosion inhibitors must be used.

For chemicals injection:

- Operations must be carried out using the necessary personal protective gear in accordance with instructions for usage of reagents.

- At the work site of the aggressive chemicals injection (sulfuric, hydrochloric, fluoric acid) should be: emergency stock individual protective gear; stock of clean fresh water; neutralizing components for the acid (chalk, lime, chloramine).
- Chemical residues should be collected and shipped to a designated area equipped for disposal or destruction of the reagents.
- After the chemicals injection or other harmful substances prior to disassembly of the injection system, an inert liquid should be pumped in a volume sufficient to flush the injection system. Liquid discharge after the washing should be carried out in a collecting tank.
- In order to determine the concentration of sulfuric acid and sulfuric anhydride vapors, the brigade should be supplied by gas analyzers.
- The loading of the thermal reactor must be carried out immediately before it is launched into the well.
- The loaded thermal reactor, tanks and work places should be located at a distance of at least 10m from injection pipelines and tanks with acids for onshore operations.

Failure liquidation operations, fishing operations.

- The complications arising during geophysical operations related to stick of the cable, well instruments or goods should be liquidated under the supervision of a responsible for geophysical operations person, with participation of the drilling crew.
- If it is not possible to eliminate sticking by reciprocating the cable, a special act should be made and delivered to the technical management of the organization responsible for the well.
- Accidents are liquidated in cooperation with a contractor organization, a drilling contractor and the executor of geophysical works using the technical means of both sides.

- Prior to the equipment descent into the well, sketches of all non-standard assemblies of the equipment and emergency tools must be prepared.
- To extract the tool or cargo from a well, a fishing tool corresponding to the design of the protective cap of the cable lug must be used. When the cable is left in the borehole, its drilling out is permitted only after all the other possible methods of extracting were not successful and further fishing operations are inappropriate. The fishing tool is provided by the drilling contractor in agreement with the geophysical organization.
- In case of blow-out evidences the well must be immediately sealed.

2. Federal norms and rules for the HSE “The Safety rules for offshore facilities of oil and gas complex”, approved by the Decree of Rostekhnadzor, March 18, 2014 № 105 (valid since May 7, 2015). In Russian: Федеральные нормы и правила в области промышленной безопасности "Правила безопасности морских объектов нефтегазового комплекса".

All three chapters were considered:

I. General provisions;

II. Design, construction and operation requirements;

III. Management of technological processes requirements.

3. Federal norms and rules for the HSE “The Industrial Safety rules for hazardous facilities with equipment operating under pressure”, approved by the Decree of Rostekhnadzor, March 25, 2014 № 116. In Russian: Федеральные нормы и правила в области промышленной безопасности "Правила промышленной безопасности опасных производственных объектов, на которых используется оборудование, работающее под избыточным давлением".

Chapter 13. Risk analysis

13.1. Risk classification

Offshore operations in ice conditions cause a broad variety of risks, requiring a structured and multi-faceted management strategy. The main risks are technical, weather-related, operational, environmental, reputational, and personnel-related.

Technical risks

Some of the major technical risks are due to:

- Low or high temperatures – impacting upon material properties;
- Sea ice – ice loads, ice in waves;
- Marine icing – impairment of safety equipment, stability issues;
- Atmospheric icing - covering radars, antennas etc.;
- Weather, communication and operational decisions;
- Rough sea;
- Uncertain metocean data – unpredictable weather forecasts;
- Visibility - fog hampering helicopter operations and ship-to-ship operations.

Safety risk

It is essential to develop evacuation and rescue procedures and equipment that are suitable for Northern Caspian Sea conditions, ensuring a crew's survival until external assistance arrives.

Environmental risk

One of the main issues of concern is a large oil spill – a risk that is increased by greater shipping and oil and gas activity in the region. The ecosystem has a slow reproduction rate, meaning it would require a longer period of time to recover from a spill. Main options in the response toolbox – including mechanical recovery, dispersion application, in-situ burning and remote sensing – should be considered and evaluated in an objective way.

Reputational risk

Accidents and incidents lead to public attention and brand damage. Good risk management, communication about risk management and general stakeholder communication is therefore essential to safeguard reputation [11].

13.2. System description

We should take into consideration two offshore systems: holding ship on the position (dynamic positioning, mooring) and hoses/coiled-tubing – X-mas tree/BOP system.

We should evaluate following types of risks during operation execution [4]:

- Risk to health and safety of people;
- Risk to environment;
- Risk to assets;
- Risk to reputation.

13.3. Qualitative accept criteria and risk matrix

Risk value = Probability rating **x** Impact score

Table 13.1 – Risk matrix example.

Impact score (severity)		Probability rating (likelihood)				
		Very unlikely	Unlikely	Possible	Likely	Very likely
		1	2	3	4	5
Negligible	1	1 (Low)	2 (Low)	3 (Low)	4 (Low)	5 (Medium)
Slight	2	2 (Low)	4 (Low)	6 (Medium)	8 (Medium)	10 (High)
Moderate	3	3 (Low)	6 (Medium)	9 (Medium)	12 (High)	15 (High)
High	4	4 (Low)	8 (Medium)	12 (High)	16 (High)	20 (Very high)
Very high	5	5 (Medium)	10 (High)	15 (High)	20 (Very high)	25 (Very high)

Qualitative accept criteria:

- 1-4 = **Low** risk (acceptable risk);
- 5-9 = **Medium** risk (ALARP-as low as reasonably practicable, risk mitigation measures);
- 10-16 = **High** risk (not acceptable risk);
- 20-25 = **Very high** risk (not acceptable risk).

Main risks during operation:

1) Collision with other vessels;
2) High heave motion, strong winds, storms;
3) Unexpected currents;
4) High ice concentrations during winter season;
5) Collapse of the riser or coiled-tubing;
6) Human factor. Low level of education and experience of the crew/intervention staff;
7) Dynamic positioning lost;
8) Bad management;
9) Weather forecast error;
10) Poor fastening of the equipment;
11) Loss of stability;
12) Lack of fuel;
13) Error during shut-in or with BOP;
14) Unappropriated operation design;
15) Fuel spill;
16) Fracturing fluids spills;
17) Oil spill.

Table 13.1 – Risk matrix for considered risks.

Impact score (severity)		Probability rating (likelihood)				
		Very unlikely	Unlikely	Possible	Likely	Very likely
		1	2	3	4	5
Negligible	1		12			
Slight	2					
Moderate	3		15, 16	8		
High	4		6, 9	3, 4		
Very high	5	11	10, 13, 14, 17	1, 5, 7	2	

Risks during hydraulic fracturing operation in fracturing equipment and in the reservoir are not considered in the project, but will be considered in my master's thesis and further concept development.

13.4. Bow-tie analysis

Bow-tie diagrams are a simple and effective tool for communicating risk assessment results to employees at all levels. The diagrams clearly display the links between the potential causes, preventative and mitigative controls and consequences of a major incident. Bow-tie diagrams may be used to display the results of various types of risk assessments and are useful training aids [53].

13.4.1. High heave motion risk

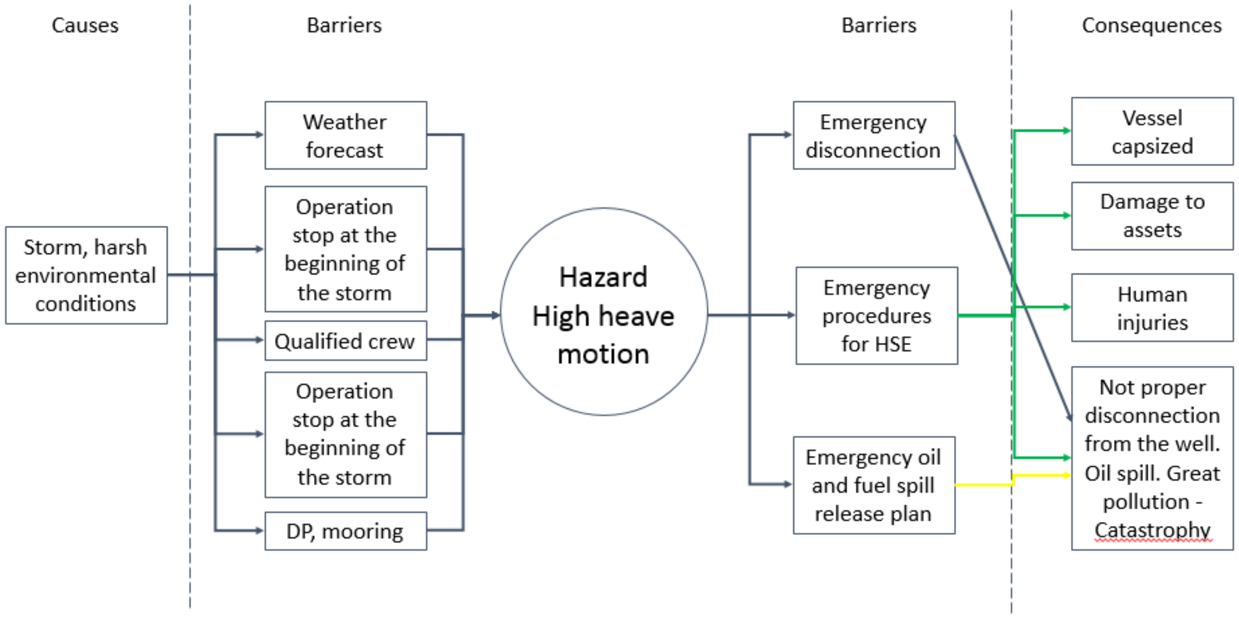

Figure 13.1 – Bow-tie analysis for the risk of high heave motion.

13.4.2. Spills of mud, fuel and fracturing fluids risk

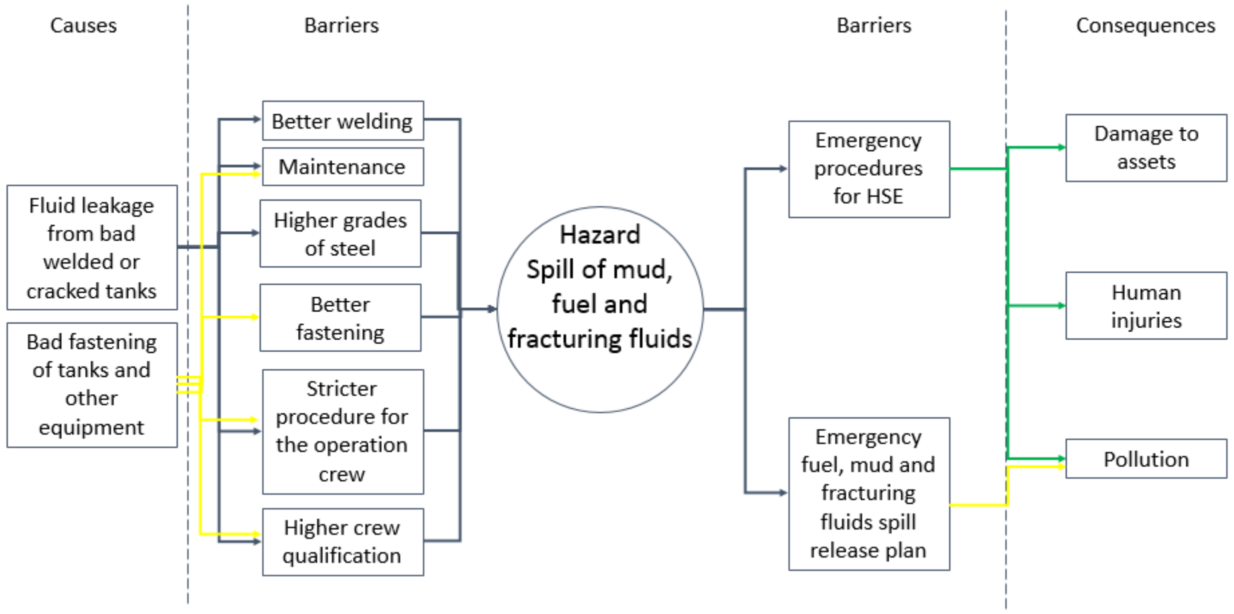

Figure 13.2 – Bow-tie analysis for the risk of spills of mud, fuel and fracturing fluids.

13.4.3. Collision with other vessels

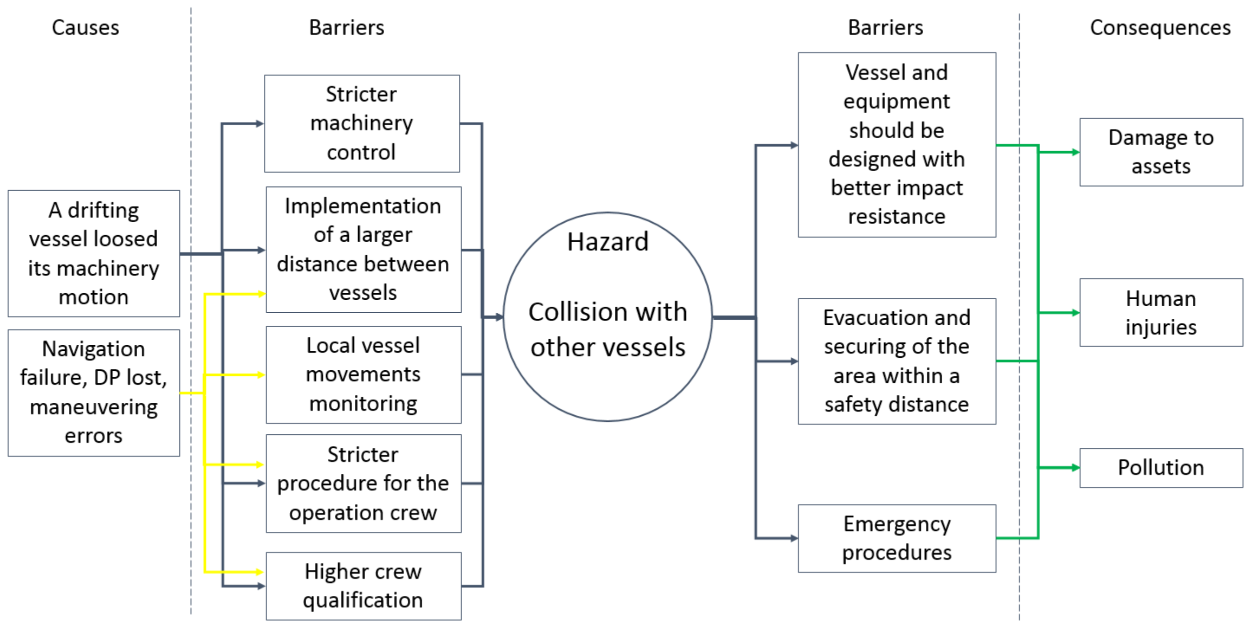

Figure 13.3 – Bow-tie analysis for the risk of collision with other vessels.

Conclusions

In this master thesis, I proposed the concept of a vessel for hydraulic fracturing and well interventions in Northern Caspian Sea conditions during summer and winter navigation period.

In the first part of the integrated approach a thorough analysis of the operating vessels was conducted. In addition, world's experience was analyzed and taken into account. Environmental conditions such as currents, waves, icing and unstable hydrological regime were analyzed as the most important factors affecting offshore field development and ice-resistant facilities design. Logistic analysis was provided. As a result, the suitable vessel was chosen.

Operational limits summary:

1. Environmental conditions.

Icing, waves, winds, currents, unstable hydrological regime should be considered during operation design stage, their influence on stability of a vessel and safety of operations must be properly evaluated. Reliable weather forecast should be provided. An emergency response plan should be drawn up.

2. Logistics according to vessel dimensions.

Vessel dimensions are limited by locks' parameter on rivers, their maximum depth and height of bridges.

3. Very limited world experience, almost no experience in Russia.
4. Lack of technology.
5. Geological and reservoir uncertainties.
6. Complex operation.
7. Limited deck space.
8. High center of gravity of the used equipment affects stability.
9. Maximum deck load limit equal 5 t/m^2.
10. Equipment availability.
11. Fragile environment and ecosystem.

Hydrostatics calculations and cross curves of stability were retrieved from the Free!Ship software. Model made in this program is based on the default model of tug with corrections due to real Arcticaborg parameters.

Ice resistance calculations were conducted to evaluate the icebreaking opportunities of the vessel.

All risks during marine operation execution were considered and mitigation measures were proposed. Lessons learnt from previous operations in the world were studied and conclusions for further concept development were made.

The master thesis was carried out in conditions of limited initial data. Obtained results can be used for further concept development.

Further work.

The worthiness of this project cannot be judged solely. Improved initial stability analysis is required.

Damage stability should be also taken into consideration for further concept development. Initial and dynamic stability cannot fully describe the vessel behavior in damaged condition. Proper calculations and analysis of damage and dynamic stability are the next step of concept development.

This thesis has only explored the vessel’s capabilities during work in the Northern Caspian Sea. Arcticaborg can operate global over its life and the motion parameter while working in other parts of the world with different sea states should be precisely analyzed.

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