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Writer: Aleksei Gorodishenin	.... (Writer's signature)

Faculty supervisor: Professor Ove Tobias Gudmestad (University of Stavanger)

External supervisor(s): Professor Anatoly Borisovich Zolotukhin (Gubkin University)

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USE OF SUBMARINES AS FIELD DEVELOPMENT FACILITIES

Gorodishenin Aleksei Anatol'evich, *master student*.

Faculty of Science and Technology, University of Stavanger

Faculty of Oil and Gas Field Development, Gubkin University of Oil and Gas, Moscow

Abstract

Today, it becomes clearer that the era of easy to extract oil is almost gone. Thus, the oil and gas industry starts to face the development of complex deposits located in deep and ultra-deep waters or in the Arctic region, often under the ice. This thesis has focused on the second type. So, it is necessary to find the most effective solutions for the field development in the ice infested waters where the ice-free is short. One of the possible answers can be the transfer of different technologies from other industries.

Such kind of technology may be taken from the military industry. Of course, we are talking about submarines. This thesis considers submarines and their possibilities as solutions for challenges in the Arctic environment. Nowadays, diesel-Stirling-electric submarines do their job in a way with minimum risks to the operator, the environment, and the crew.

The main idea of this paper is to show that submarines can be used as a mothership or, in simple words, a carrier for ROVs, which application is very versatile, but the core purpose is to maintain the field operations during the production phase. To show that it is possible, the design of submarines will be considered with an accent on special room for ROVs and the compartment for its running in the water. Nevertheless, submarines can perform simple tasks like installation, inspection, maintenance, and repair by itself with a help of an on-board gantry crane. Risk analysis will also be included to prove that the idea of submarine utilization is safe for everyone.

The ice surfacing is included in the analysis. The design of the submarine is performed so that it has a sail. In a case when the submarine breaks the surface, initially

ice breaks at the point of the contact of a sail with the bottom layer of ice and as a consequence, stress will be created at the point of the contact, and then the ice will break due to bending.

For changing the crew of the submarine, it is sufficient that the submarine ascends so that the sail is on the ice, and not necessarily that the submarine breaks the surface completely. It is important to remember that a submarine cannot break too thick ice because capabilities of the submarine are limited. To solve this problem a special equipment is installed on the submarine like an ice profiling sonar. The sonar searches the ice for a thickness the submarine could break in a place where the crew landing is required. Usually, it is the ice with a thickness not exceeding 1,5 meters although. It depends on the size, mass, and geometry of the submarine.

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List of abbreviations

AIP – air-independent propulsion;

CNG – compressed natural gas;

IRM – inspection, repair, maintenance;

LARS – launch and recovery system;

MBES – multi-beam echo-sounder;

ROV – remotly operated underwater vehicle;

SSS – sensors and sensing system;

TMS – tether management system;

VAC – voltage alternating current;

List of symbols

$A - added\ mass;$

$A_{transit}$
$- energy\ for\ the\ transition\ to\ the\ field;$

A_{rest}
$- energy\ for\ the\ rest\ of\ operation;$

$A_{mission} - whole\ energy\ requirement;$

$b_{reserve} - reserve\ buoyancy;$

$C_D - drag\ coefficient;$

C_{stores}
$- daily\ stores\ consuption\ per\ person;$

$D_{airlock} - airlock\ diameter;$

$F_{drag} - drag\ force;$

$f_{utility} - utility\ factor;$

$g - gravity\ acceleration;$

$H - cargo\ height;$

$Hp - pumping\ head;$

$H_{ROV} - ROV\ height;$

$h - hull\ thickness;$

$K_p - factor\ which\ is\ responsible$

$for\ the\ submarine\ form;$

$L - cargo\ lenght;$

$L_{airlock} - airlock\ lenght;$

$m_s - submerged\ weight;$

$m_{stores} - stores\ weight;$

$N_{crew} - crew\ size;$

$N_d - \ number\ of\ days;$

$\eta_s - transmission\ efficiency;$

$\eta_{saf} - safety\ coefficient;$

$\eta_H - hull\ efficiency;$

$\eta_o - propulsor\ efficiency;$

$\eta_{tp} - trim\ pump\ efficiency$

$P - operation\ pressure;$

$P_s - submersion\ deph\ pressure;$

$\rho_{air} - air\ density;$

$\rho_w - sea - water\ density;$

$(\rho_{max} - \rho_{min}) - required\ range\ of\ sea$

$water\ density;$

$Q - volumetric\ flowrate;$

$r - radius\ of\ half\ sphere$

$under\ the\ cube;$

$rh - hull\ radius;$

$\sigma_{vM} - von\ Mises\ yield\ criterion;$

$\sigma_y - yield\ strenght;$

$\vartheta - lifting\ speed;$

$\vartheta_c - submarine\ speed;$

$V_{airlock} - airlock\ section\ volume;$

$V_{El\&Com}$
$- volume\ of\ electronics\ and\ communications;$

$V_{cargo\ storage} - volume\ of\ cargo\ storage$

$V_{studio} - ROV\ studio\ volume;$

$V_{payload} - payload\ volume;$

$V_{form} - submarine\ volume;$

$V_{prHull\ IN} - pressure\ hull\ inner\ volume;$

$V_{prHull\ OUT} - pressure\ hull\ outer\ volume;$

$V_{trimTanks} - summary\ volume\ of\ trim\ tanks(precalculation)$;

$V_{trimTanksNew} - summary\ volume\ of\ trim\ tanks$;

$V_{CNG} - required\ volume\ of\ CNG$;

$V_{fuelTank} - fule\ tank\ volume$;

$W_{ROV} - ROV\ width$;

$W_{eff} - effective\ power$;

$W_{motor} - motor\ power$;

$W_{hotel} - hotel\ load$;

$W_{effST} - effective\ stationkeeping\ power$;

$W_{motorST} - motore\ stationkeeping\ power$;

$W - cargo\ width$;

$W_{trimpump} - tripm\ pump\ pow$

Introduction

The common way to carry out any kind of work during the oil and gas field development with remotely operated underwater vehicles in any waters is to use a support vessel with a set of ROVs on board. Such ships are very helpful, but require a calm sea with minimum waves and no ice around.

Another way is proposed by OTC-255501-MS and OTC-23742. It is a submarine, which serves as an ROV “Mothership” and has few additional functions. The main idea is that such submarines do not depend on weather conditions at the surface. Those vessels are introduced as a concept, but this work aims to propose dimensions, internal arrangements, power requirements, form, material and check, whether such mechanism has the possibility to surface through ice. Most part of work is based on the Rydill and Burcher book “Concepts in Submarine Design” as it is the most impressive compendium for a submarine designer.

The submarine considered in this thesis has the aim to be used for Shotkman gascondensate field and in the whole Russian Arctic, especially such places like Kara Sea where the ice conditions are really harsh.

To be able to implement this idea into reality, we need to answer the following questions:

1. What are the working conditions of this technology?
2. What does it represent?
3. Can we design the possible option of the technology?
4. What are the risks?

We structured the work on the basis of those questions.

Thesis organization consists of Introduction, 5 chapters and conclusion.

Chapter 1 describes the main hydrometeorologic/weather and ice conditions in the Barents Sea (with emphasis on the Shtokman field location) and the Russian Arctic shelf with an accent on its western part, where the core oil and gas projects take place.

Chapter 2 expands ideas from the introduction and abstract. It shows that it is possible to find the required crew specialists and tells the possibility of this technology.

Chapter 3 represents the core of the work and provides us with suggestions and modeling of the submarine itself.

Chapter 4 provides insight into the possibility of outer hull material to withstand surfacing through the ice surface of 1 meter thickness.

Chapter 5 gives a brief risk assessment of the technology.

1. Environmental conditions in the Barents Sea and on the Arctic shelf.

1.1. General Information.

The key area of applicability of the technology "submarine production system" is the Russian continental shelf with the ice-infested Arctic waters. Nevertheless, the thesis work is done for the entire shelf in general and for the one field in particular (Shtokman gascondensate field). Here, we will list the main environmental conditions of the Russian part of the Arctic region and the Shtokman field:

Shelf: On August 4, 2015, Russia resubmitted its bid, Figure 1 containing new arguments based on scientific data collected during many years of Arctic research, for territories in the Arctic to the United Nations. Through this bid, Russia is claiming 1.2 million square kilometers of the Arctic sea waters extending more than 650 kilometers from the shore. So, the approximate size of the Russian shelf is 1,2 million km^2 [1].

The ice conditions of the Arctic region is shown in Figure 2.

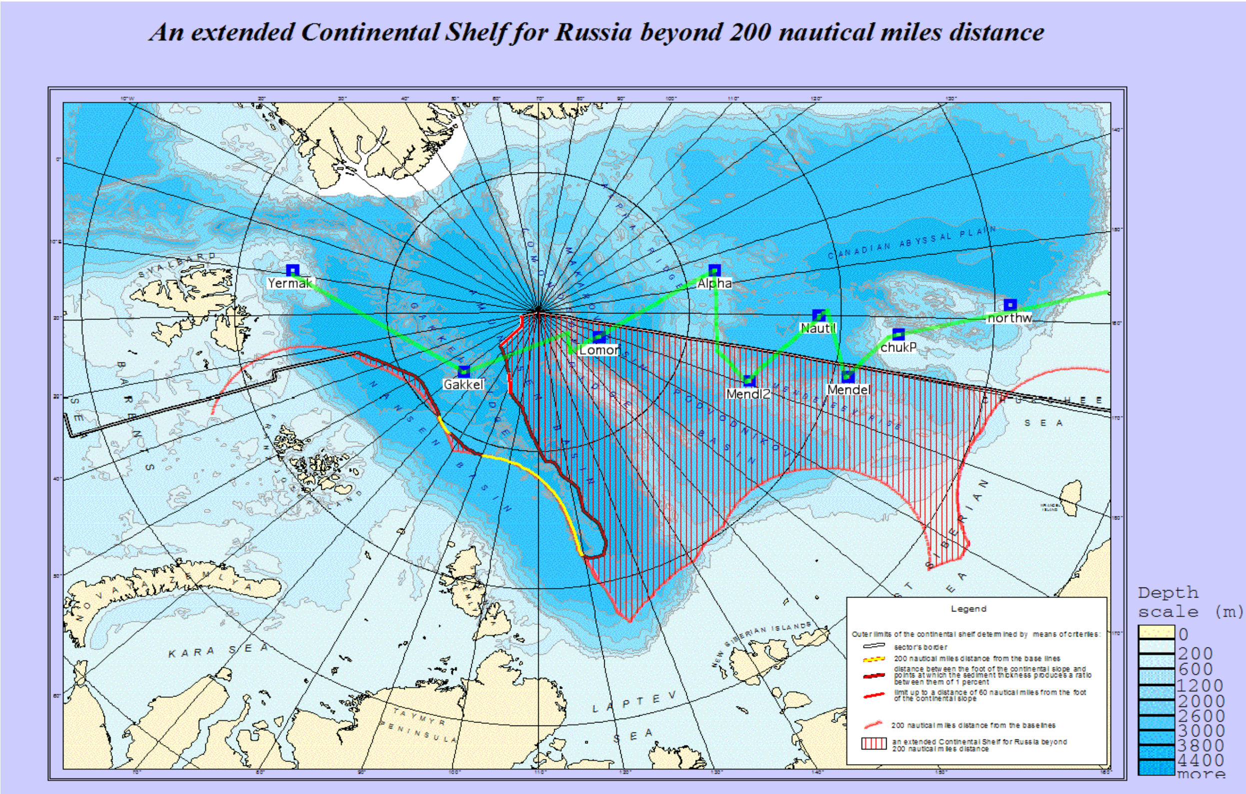

Figure 1. The territory of the Russian shelf with depths [2]

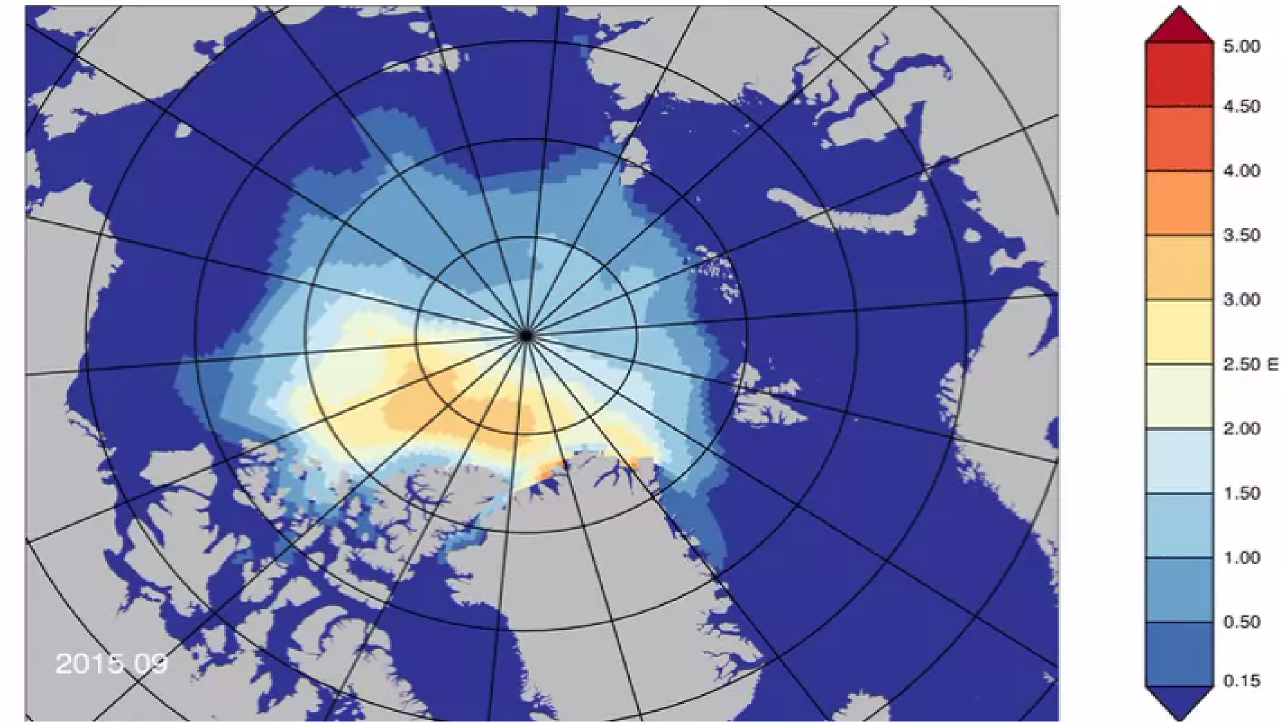

Figure 2. Arctic ice thickness (m) in September 2015 [3]

1.2. Barents Sea

The Barents Sea is a marginal sea bordering on the Arctic Ocean in the north, the Norwegian Seas and the Greenland in the west, the Kara Sea in the east and the coast of the Kola Peninsula in the south (Figure 3 and Table 1)

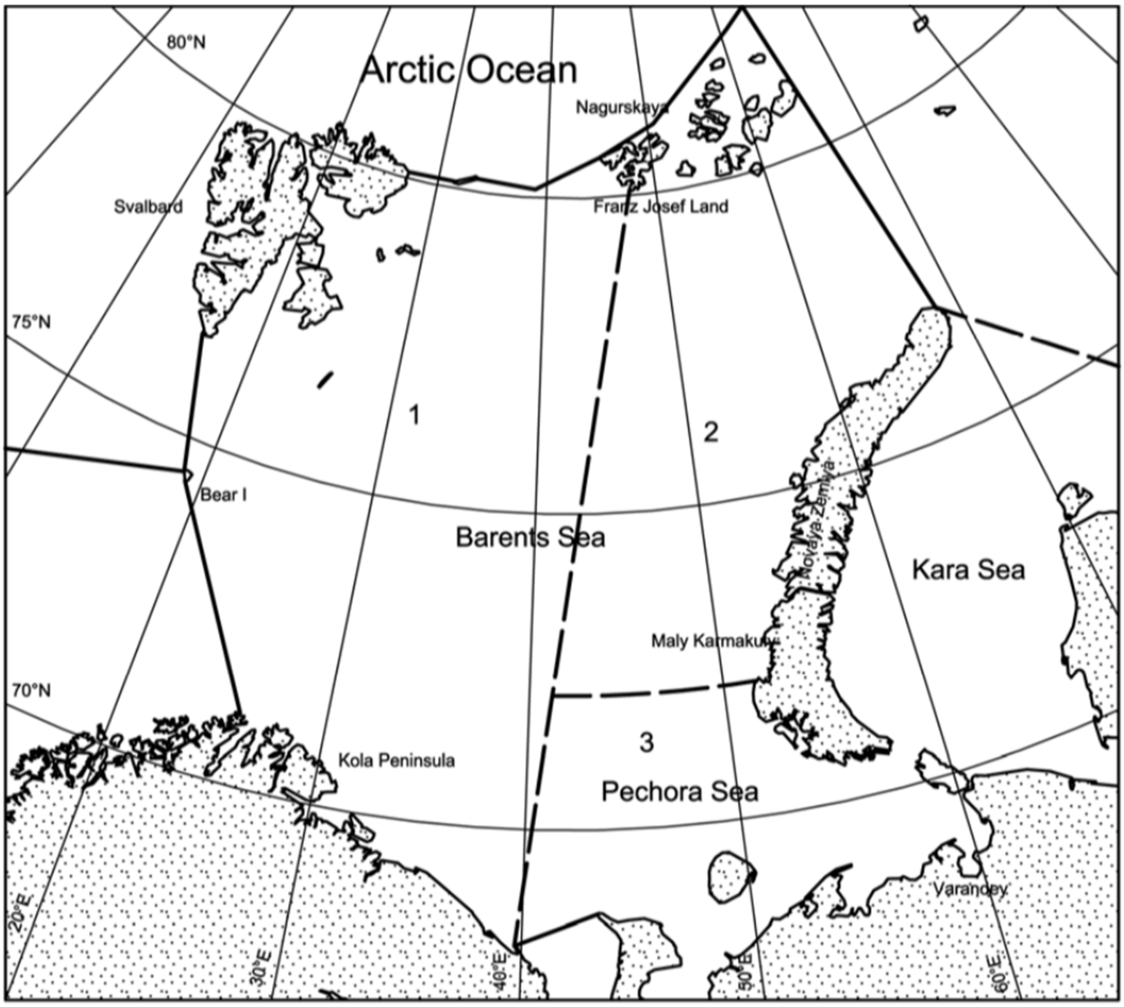

Figure 3. Boundary and regions of the Barents Sea [4]

Table 1. General information for the Barents Sea [4]

	Western Region	**Northeastern Region**	**Pechora Sea**
Area of Coverage	70^0N to 80^0N, 18^0E to 42^0E	72^0N to 81^0N, 40^0E to 67^0E	68^0N to 72^0N, 38^0E to 60^0E
Winter Season Length	12 months	12 months	October to July
Summer Season Length	None	None	August - September

The major morphometric characteristics of the Barents Sea are:

- Area = 1 424 000 km^2
- Water volume = 316 000 km^3
- Average depth = 222 m
- Deepest depth = 600 m

For the weather monitoring purposes the region is divided into the western (monitored by the hydrometeorological station located at the Bear Island), northeastern (Maly Karmakuly stations) and southeastern parts (Varandey station). This division takes into account the general physical-geographical features of the Barents Sea (seabed relief, system of currents, ice edge position and others) [4].

1.3. Climate

The location and extent of the Icelandic Low determines the character of the atmospheric circulation in the autumn and winter periods. Cyclones connected with storm winds have a very high frequency of occurrence, between 2 to 4 per month, with trajectories usually passing from Iceland either into the central part of the Barents Sea or southward. In winter, northeasterly winds predominate in the northern part of the Barents Sea and southwesterly and southerly winds predominant in the southern area.

In summer, cyclonic activity diminishes and a uniform increased pressure area forms in the Barents Sea. Cyclone trajectories move northwards passing across the Franz Josef Land archipelago and their occurrence frequency decreases on average to 2 cyclones/month. In most regions, winds are weak and unstable by direction. Storm winds occur rarely in the summer period.

The lowest annual temperature differences, of 10 °C to 15 °C, are typical of the southern area of the Barents Sea where sea ice is usually absent and southwesterly winds predominant. The largest annual temperature differences, of 25 °C to 30 °C, characterize the northern areas where the winter ice cover contributes to intensive cooling of the lower air layers while dominating northeasterly winds advent the Arctic Basin cold air masses into the region. The mean annual air temperature varies from +2 °C in the southern sea areas to -10 °C in the north of the sea [4].

1.4. Hydrology

The inter-annual and multi-year changes of the Barents Sea hydrological and ice regime are influenced by a system of stable warm and cold ocean currents.

The system of warm currents includes the South-Spitsbergen, Nordkapp, Murmanskoye, Kaninskoye, Kolguyevo-Pechorskoye and Novozemelskoye currents. The system of cold currents includes: the coastal current of the Franz Josef Land, East-Spitsbergen, Sydkapp, Bear Island, Perseus, Central and Litke currents. The White Sea and the Pechora thermo-line currents distinguished by a decreased salinity comprise a special group of currents [4].

Four main water masses have been identified in the Barents Sea [4]:

- Atlantic water with increased temperature and salinity flowing from the west in the form of surface currents and transported from the north at depth from the Arctic Basin;
- Arctic water with below zero temperature and decreased salinity flowing from the north as a surface current;
- Coastal water with a significant seasonal temperature amplitude and low salinity forming under the action of continental runoff and coastal flow of freshened waters;
- Barents Sea water with low temperature and high salinity formed within the sea because of mixing of different water masses.

Within the Barents, tides play a major role in sea level oscillations. In the western and southern areas, tides are regular semi-diurnal (surface oscillations of 2,2 m to 3,7 m), whereas in the eastern area, tides have an irregular semi-diurnal character (surface oscillations up to 4,0 m). In the meridional direction, the tidal magnitude decreases from south to north comprising only about 0,2 m in the vicinity of the Franz Josef Land [4].

1.5. Sea ice and icebergs

An important distinguishing feature of the Barents Sea ice regime is that its surface area is never completely ice-covered. During the period of the greatest ice cover, March to April, it usually covers only about 55 % to 60 % of the surface area with open water occupying the rest of the area [4] (see also figure 5).

The ice cover may be a combination of multi-year ice up to about 3 meters thick, first-year ice generally less than 1,5 meters thick, and icebergs. Basically, for the entire Barents Sea during the period of the maximum ice cover development; the fraction of multi-year ice averages 10 %, while the fraction of young ice is around 15 %.

The Barents Sea ice cover contains icebergs from the glaciers of Svalbard, Franz Josef Land and Novaya Zemlya. Icebergs drift from these glaciers under the influence of the prevailing winds and ocean currents. Entrained in the general ice drift, icebergs can move large distances during their life span. Information on icebergs and their drift is provided in tables 1 through 3 [4].

Land fast ice is established annually along most continental and island shores of the Barents Sea. The largest width and stability of land fast ice is noted in bays and inlets of the southern sea area and also among the islands of Franz Josef Land and Svalbard.

During winter, strong ice pressure very often occurs at sea and forms conglomerations such as stamukhi and ridges. Stamukhi are generated in coastal areas in water depths up to 20 m. Thus, it is not so dangerous for a submarine. The maximum sail height for these features ranges from 2,3 meters to 5 meters and keel depths of 15 meters to 20 meters. The greatest intensity of ridging is observed in the northwestern and southeastern sea areas due to the onshore drift of the ice [4].

Table 2. Barents Sea oceanographic conditions [4]

		Western region		Northeastern region		Pechora sea	
	Parameter	Average annual values	Range of annual values	Average annual values	Range of annual values	Average annual values	Range of annual values
Waves – near shore (< 100 m water depth)	Significant wave height (m)	2,7	2,0 to 10,0	2,4 to 2,7	2,0 to 9,0	2,5	1,5 to 7,0
	Range of zero-crossing periods (sec)	11,0	10,0 to 13,0	11,0	10,0 to 13,0	9,0	8,0 to 10,0

Waves – near shore (> 100 m water depth)	Significant wave height (m)	ND	ND	2,5	2,0 to 9,0	ND	ND
	Range of zero-crossing periods (sec)	ND	ND	9,5	8,0 to 10,0	ND	ND
Current	Near surface maximum speed (cm/sec)	65,0	60,0 to 70,0	42,0	31,0 to 51,5	115,0	100,0 to 130,0
	Mid layer maximum Speed (cm/sec)	ND	ND	ND	ND	30,0	20,0 to 50,0
	Bottom maximum speed (cm/sec)	ND	ND	ND	ND	ND	ND
Tidal current	Maximum surface speed (cm/sec)	35,0	30,0 to 40,0	15,0	10,3 to 20,6	35,0	30,0 to 40,0
Tide	Tidal range (total) (m)	0,8	0,5 to 1,3	0,3	0,2 to 0,6	1,0	0,5 to 3,0
Wind induced surge	Water depth range total (m)	ND	ND	1,8	1,7 to 1,9	1,5	1,0 to 3,5
Water salinity	Average surface salinity (ppt)	34,5	34,5 to 35,0	33,8	33,3 to 34,2	30,0	25,0 to 33,0
	Average mid layer salinity (ppt)	35,0	34,0 to 36,0	34,5	33,0 to 35,0	ND	ND
Water temperature	Summer surface maximum (°C)	9,0	7,0 to 11,0	2,0	1,5 to 2,5	8,0	7,0 to 9,0
	Summer surface average (°C)	7,0	5,0 to 9,0	1,5	1,0 to 2,0	7,0	6,0 to 8,0
Seabed geotechnical -	Gouge depth (m)	ND	ND	ND	ND	0,5	0,3 to 1,5

Ice induced gouge	Water depth range (m)	ND	ND	ND	ND	< 15,0	< 20,0
Seismic	Magnitude	ND	ND	ND	ND	ND	ND

Table 3. Barents Sea sea-ice conditions [4]

		Western region		Northeastern region		Pechora sea	
	Parameter	Average annual values	Range of annual values	Average annual values	Range of annual values	Average annual values	Range of annual values
Sea ice							
Occurrence	First ice	All year	All year	All year	All year	25 October	20 October to 5 July
	Last ice	All year	All year	All year	All year	5 July	25 June to 15 July
Level ice (first year)	Land fast ice thickness (m)	1,4	1,3 to 1,5	1,5	1,4 to 1,6	1,0	0,9 to 1,1
	Floe thickness (m)	1,3	1,2 to 1,4	1,4	1,3 to 1,5	0,8	0,7 to 0,9
Rafted	Rafted ice thickness (m)	0,4	0,3 to 0,5	0,4	0,3 to 0,5	0,4	0,8 to 1,0
Rubble fields	Length (m)	ND	ND	ND	ND	ND	ND
	Sail height (m)	ND	ND	ND	ND	ND	ND
Ridges (first-year)	Keel depth (m)	17,5	15,0 to 20,0	15,0	14,0 to 16,0	16,0	15,0 to 18,0
	Sail height (m)	4,7	4,5 to 5,0	4,2	4,0 to 4,5	3,5	3,0 to 18,0
Stamukhi	Water depth range (m)	< 20	< 20	< 20	< 20	< 15	< 20

	Sail height (m)	3 to 5	8 to 10	3 to 5	8 to 10	3 to 5	10 to 11
Level Ice (second and multi-year)	Landfast Ice thickness (m)	2,5	2,2 to 2,8	2,5	2,2 to 2,8	None	None
	Floe thickness (m)	2,7	2,5 to 3,0	2,8	2,5 to 3,0	None	None
Ridges (second and multi-year)	Sail height (m)	ND	ND	ND	ND	None	None
	Keel depth (m)	ND	ND	ND	ND	None	None
Rubble Field (second and multi-year)	Av. Sail height (m)	ND	ND	ND	ND	None	None
	Length (m)	ND	ND	ND	ND	None	None
Ice movement	Speed in near shore (m/s)	0,5	0,4 to 0,6	ND	ND	0,7	0,6 to 0,8
	Speed in offshore (m/s)	0,6	0,5 to 0,7	0,5	0,4 to 0,6	ND	ND
Icebergs							
Size	Mass (tonnes)	Up to 6000000	0 to 10000000	Up to 4000000	0 to 5000000	ND	ND
Frequency	Month present	Jan to Jun	Jan to Jun	All Year	All Year	Infrequent Occurrence	Infrequent Occurrence
	Number per year	10 to 40	10 to 40	ND	ND	ND	ND
	Maximum Number per Month	30	0 to 30	ND	ND	ND	ND

1.6. Environmental conditions of the working areas

Shtokman: The area, Figure 4, of the field situated in the central part of the Barents Sea, it is 560 km from the port of Murmansk and 320 km from the Nordsheld archipelago. The deposit area is confined to the south western of the extended tip (more than 120km) and to the rather narrow seabed hill elongated generally north-north-easterly direction. The sea depth varies from 280 to 320-350 m at the top of this hill, and its slopes reach 350 - 390 m. The water depth of the field is around 310-380 m.

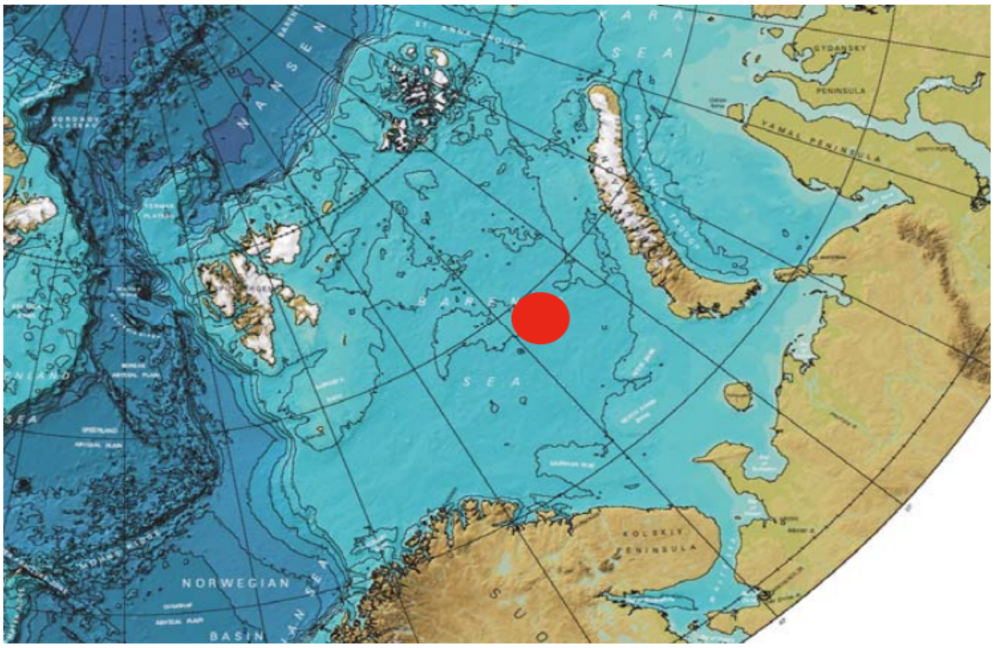

Figure 4. The Shtokman gas and condensate field [5]

1.7. Ice conditions, Figure 5

Shtokman: Annual ice can appear in the area of the field in some years, usual it is brought into the area from the northern areas of the Barents Sea. In terms of long-term period, appearance of ice in the area of the Shtokman can take place in April (about 25%).

The most unfavorable period in respect of the ice can be considered the period from March to June; the least dangerous is from August to December. There are no local ice in the field area. Apart from drifting ice, it is possible to find icebergs produced by the glaciers of Novaya Zemlya and Franz Josef Land [6].

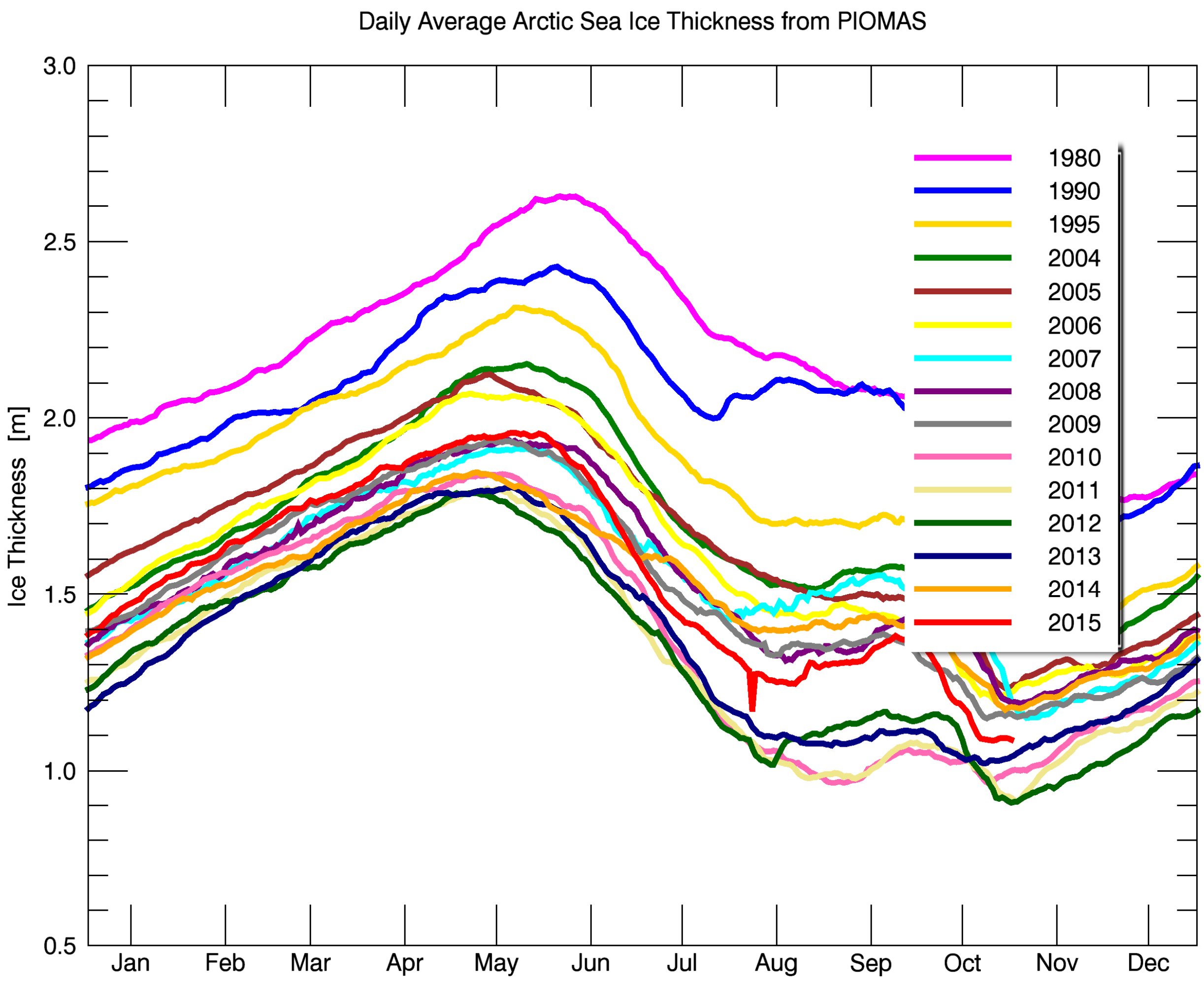

Figure 5. The average ice thickness of the areas close to Nord Pole from the Russian site [3]

1.8. Currents

Shtokman: There are tidal and persistent currents in the area of the field. The velocities of tidal currents do not exceed 10-25 cm/sec typically. The Murmansk warm current largely shapes the persistent currents in the project area [7].

To summarize submarines modeled for working in this region exist. And it is important to keep in mind that our submarine will perform operations to control and manage ROV`s works in the Shtokman field area.

2. Possibility of using submarines in the oil and gas industry

2.1. Possibility of a submarine as mothership

Typically, ROVs transition and keeping are the work of an ROV support vessel (see Figure 6), but in the ice-infested region, such ships must have capability for ice cleaning in the working zone if the ice is not so thick, otherwise the necessity of icebreakers is indisputable. The investments can be too high and even in the case of such project, there is no guarantee that everything will go smoothly.

Figure 6. Typical ROV support vessel – Fugro Aqurius [34]

Thus, we should find another approach to solve the problem. If ROVs are launched beyond the sea surface from a depth where ice and currents almost have no impact, it will provide a solution for the problem. Such mechanism can be named submarine, but it is not the military one with torpedoes and silent machinery. This submarine has a civil purpose like ROVs and crane operations.

The ROVs have been instrumental in the development of offshore fields. From drilling (where the ROV is used to monitor the block of preventers’ operations or riser itself), through construction support (interfacing, surveys), Inspection Repair Maintenance (inspection, tooling) and in the decommissioning stage the ROV could be the safest way to operate in the subsea environment [29].

This submarine can be helpful on different stages of field developments.

Figure 7. ROV is doing construction support [29]

In construction activities (Figure 7), the ROV units are very often an important part of the operation itself and are required to move objects into the point and observe the process of construction. The ROV can keep its position to the structure. The functionality that allows the system move to desired positions, to track and observe structures at the touch of one button can be relied upon to speed up all ROV processes.

An ROV may serve as a survey tool. Side-scan, video and multibeam sonars are used to draw the map of the seabed. The data from the navigation sensors can be used to position and geo-reference the data and precise seabed maps can be drawn in this way.

The main application of the ROV is IRM. Risers, Chains, Flow Lines, manifolds and wells are the objects of inspections. The ROV ensures stability of a platform for survey sensors (e.g. SSS, MBES). Changing the old or broken parts of the equipment can be done in a short time.

Additional application of high class ROVs are trenching for cable laying and, as it was mentioned above, monitoring during drilling operations (drilling support) [29].

2.2. Crew size

Crew size must be as minimum as possible due to limited space and food/water consumption, thus, we propose the option:

- 1 captain of the vessel;
- 1 mate (captain assistant);
- 1 supervisor;
- 1 ROVs mechanic
- 1 ROVs pilot;
- 5 sailors;
- 1 person responsible for the crane;
- 3 men for cooking and cleaning stuff;

Total: 14 persons.

A captain ensures that the ship complies with local and international laws and also complies with the corporate policies. The captain is responsible, under the law, for aspects of operation like the safe ship navigation, its cleanliness and seaworthiness, safe handling of all cargo, management of all personnel, inventory of ship's cash and stores, and maintaining the ship's certificates and documentation. There are a lot of other things the captain shall do, but they are common for the civilian fleet [35]. A mate helps the captain to carry out duties.

Sailors are responsible for submarine location, moving, submerging and repairing. A supervisor observes all lifting, well, pipeline and so on operations. ROV pilots and mechanics should know basics of each other's work for substitution.

According to 3.10.2, we can understand that typical mission length is 32.5 days. The crew may work a full monthly shift or change every two weeks. All the work should be suspended, and the submarine has to surface through the ice in the case of crew changing. Such operation requires huge economic investment. Therefore, it is better to send people for 32.5 days.

Change of the crew can be done in the next way:

1. The closest point to the Shtokman field is the Nordsheld archipelago (part of Novaya Zemlya, so there must be the transshipment base. It has to be like Varandey's station, but smaller.
2. People arrive at the base from Arkhangelsk by a plane.
3. The submarine sends the location of surfacing.
4. New crew are transported to the point with help of a MI-8 helicopter, which is capable of flying more than 1000 kilometers.
5. A helicopter lands on the one-meter ice with running engines and holds most of the vehicle weight with help of its own resources.
6. Old crew goes back to the Nordsheld archipelago.
7. People arrive to Arkhangelsk by a plane.

According to 3.11, the submarine can operate only for 32.5 days and should return back to Murmansk or Vidyayevo ports for refueling process.

We can understand from the chapter 3 that the submarine is filled with the different kind of materials for all 32.5 days. Thus, it does not require addition supplies. The food stock, air regeneration device (Russian: УЭРВК), water supply and so on are inside the submarine.

3. Submarine configurations

3.1. Submarine basics

Usually, the submarine is a military vessel with the main purpose of doing hostilities during wartime at the sea surface or underwater. Modern submarines are capable of staying underwater for a long time. (See Figure 8)

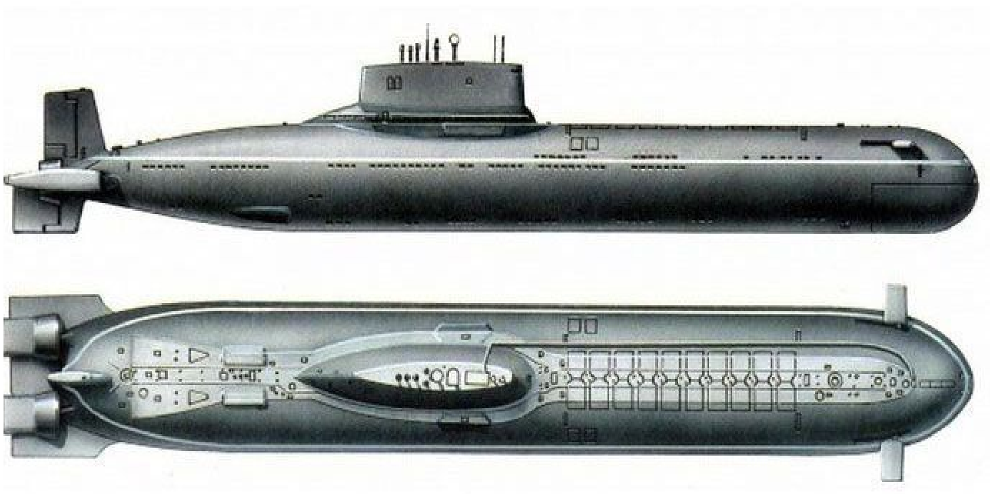

Figure 8. Project 941 - Akula (NATO - Typhoon)

There are also special submarines for the transport, rescue and experimental work. Design of the first two groups is very controversial. For example, there were only two rescue submarines built. (See Figure 9)

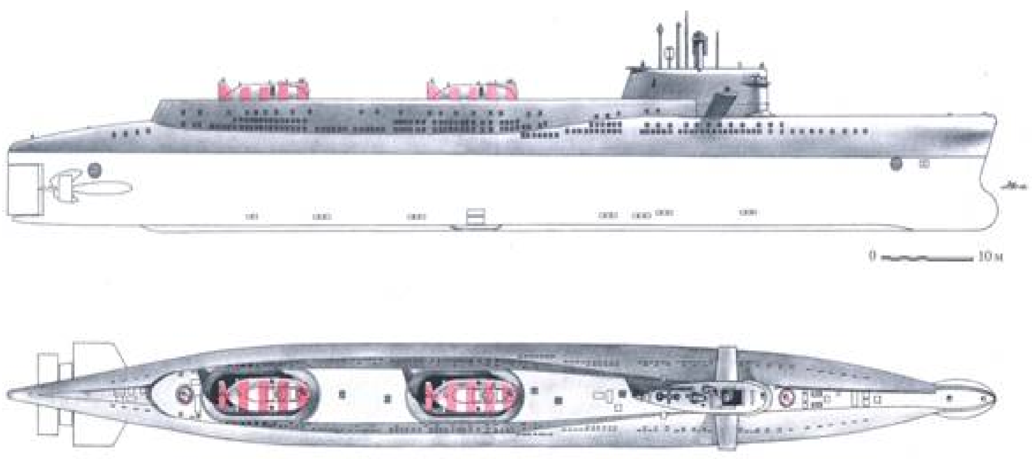

Figure 9. Project 940 – Lenok (NATO – “India”)

By the water displacement, submarines can be divided into significant(3000 – 8000 m^3 or more), big (1500 – 3000 m^3), average (500 – 1500 m^3) and small (150 – 500 m^3). The submarine from this project belongs to the mean one.

Basically, submarines have two hulls: pressure and outer.

Pressure hull

It is a waterproof part of a submarine capable of withstanding an outer pressure of the water at the maximum submersion depth. The crew, weapons, machinery, computers, storages and so on are located here. During the immersion process, a pressure hull withstands big pressure impact.

The pressure hull represents a circle in the transverse section because such design meets the load conditions in the best way. Pressure hull consists of sheathing and a framework. Sheathing consists of steel plates with a thickness that depends on the diameter of the pressure hull.

The framework is the basis of a submarine. It consists of frames and provides stability of the construction.

Frames are made in half circle shape connected by welds.

Outer hull

The outer hull adds seaworthiness to the submarine and serves as a place for tanks, systems and different equipment.

The outer hull consists of aft and fore extremities, deck superstructure and sail. A framework of the hull is made of a rigid frame which includes ordinary frames and transverse bulkheads.

Sheathing is designed in a way to withstand waves and to provide impermeability of the tanks.

In the lower part of the outer hull, a linked fin is installed all over the length of the hull to connect outer and pressure parts. Also, a linked fin saves the outer hull from damage during the mooring process.

There are five groups of the depths regards for the submarine:

- Periscope depth (8-12 meters) is the depth where a submarine can use a periscope for the sea surface observing and uses radiotechnical devices.
- Safe depth (30-40 m) is the lowest depth where a submarine can safely sail without collision with surface ships. Those two groups should be passed as soon as possible to avoid accidents.
- Maximum depth is the depth where a submarine can sail for a short time without any hull deformation.
- Working depth (70-90% of maximum) is the depth where a submarine can operate constantly.
- Estimated submersion depth. Hull is designed for this type of depth [20].

3.2. Hull

Recently, it has become ordinary to build submarines with single and double hull. Every nation continues to follow each own school of construction. When USA prefers single hull, Russia gives preference to double hull.

Now, we are going to discuss every type of existing hulls.

Single hull: The pressure hull forms outer hull; the ballast tanks are placed in the aft and fore of the submarine, and inside the pressure hull if submergibility is required. (See Figure 10, first submarine)

Double hull: the outer hull protects the pressure hull which is located inside. The main ballast tanks are inside the space between the hulls. (See Figure 10, second submarine)

Mixed hull: alteration of the single and double hulls along the submarine. (See Figure 10, third submarine)

Multi-hull: the pressure hull is protected by few outer hulls. This type is usually used in transport type submarines. (See Figure 10, fourth and fifth submarines)

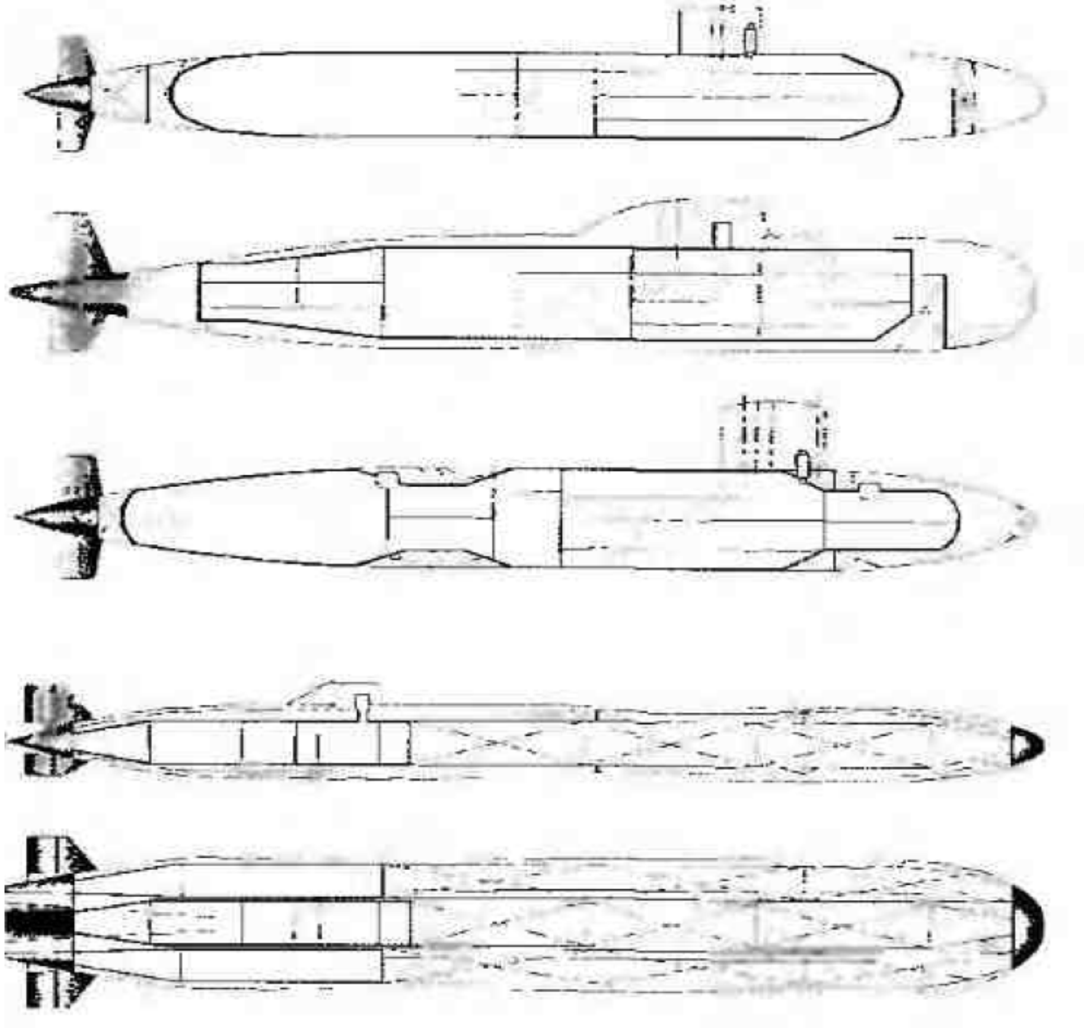

Figure 10. Hull configurations [8]

We believe that single hull is the best option for this thesis due to next reasons:

1. Less power requirements and perfect submerged dynamic stability.
2. The vulnerability of the hull and necessity of ballast tanks reinforcement are the weak points of this configuration, but it can be considered as weakness only if we are going to build a military submarine, but this project is referred to a civil one.
3. Easier to design compared to other hull configurations [9].

3.3. Sail

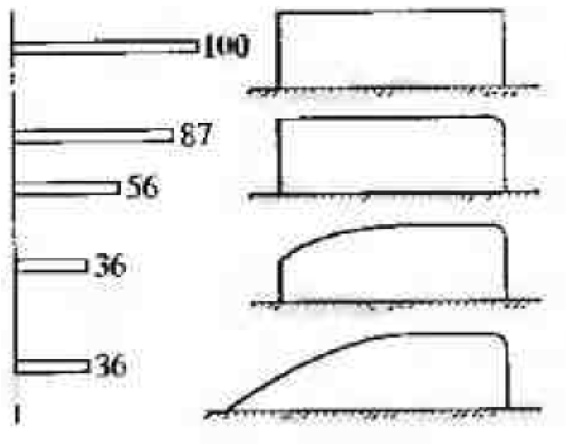

Figure 11. Sail configurations versus resistance [8]

Figure 11 provides a good explanation for choosing a blended type of sail; the recommended sail does not require so much equipment inside as compared to a military one. It is essential to mention that sail resistance plays a quite small role inside the whole picture, so the sail choice is mainly determined by the amount of equipment and the school of construction.

The sail will contain typical equipment like an emergency position-indicating radio beacon station, a raft, a mooring device and a periscope. 40 m^3 must be enough to accommodate all equipment and use it as a vertical stabilizer..

3.4. Shaft

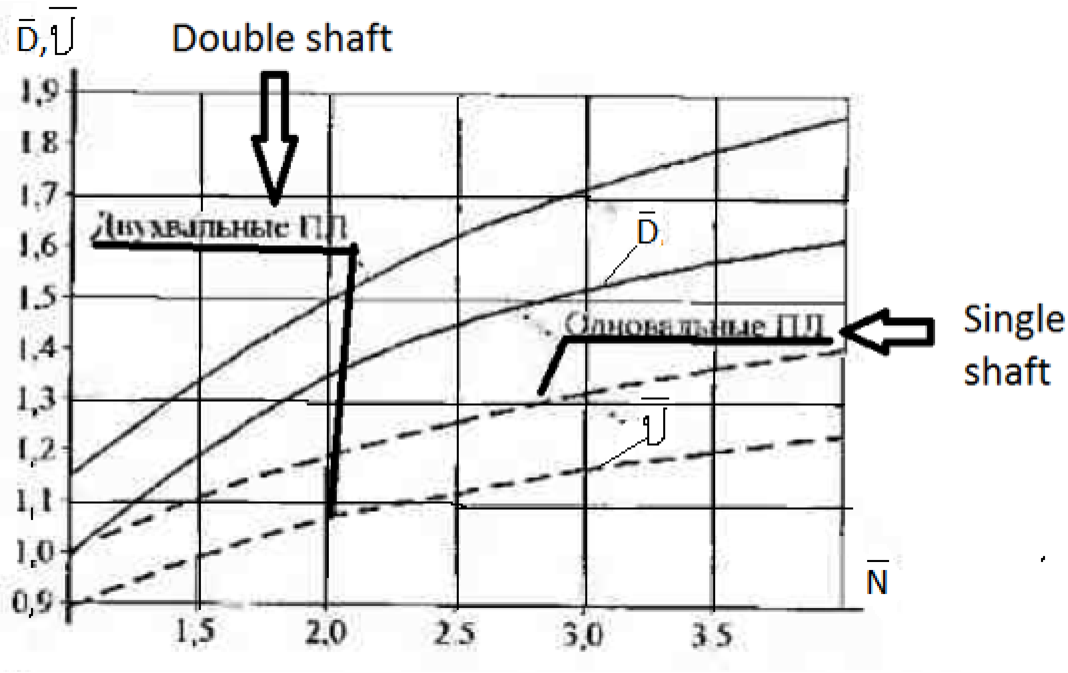

Figure 12. Speed versus power

$\bar{N} - relative\ power\ of\ the\ main\ power\ source, D - relative\ displacement,$

$\bar{\vartheta} - relative\ full\ speed\ of\ the\ submarine, \bar{\vartheta} = 1\ is\ the\ speed\ of$

$the\ single\ shaft\ submarine\ with\ \bar{N} = 1$ [8].

Based on the main feature of submarines briefly described above we assume that an individual shaft is the best option. Here are the main reasons:

- the hull efficiency of the single shaft submarine is around 1.05-1.20 and it helps to increase the propulsion coefficient to 0.75-0.8 when the double shaft's is around 0.6, Figure 12
- a single shaft beats the dual shaft in the prevailing number of parameters except the life cycle and the maximum speed with a limited power source [8].

3.5. ROV

3.5.1. ROV selection

The good option is 2 ROVs of Saab Seaeye company: 1 SEAEYE FALCON DR and 1 SEAEYE PANTHER-XT PLUS. Here are the characteristics of each ROV (Table 4):

Table 4. ROVs Characteristics

Parameter	Falcon DR	PANTHER-XT PLUS
System power requirements	Sing phase 100-270 VAC at 2.8 kW	3-phase 380-480 VAC at 100 kW (including TMS, Tooling, LARS and cabin)
Maximum umbilical length,m	1100	1100
Depth rating,msw	1000	1000
Length,mm	1055	2140
Height,mm	635	1217
Width,mm	600	1060
Launch weight, kg	100	800
Forward speed, knots	>3	>4
Thrust forward, kgf	50	353
Thrust lateral, kgf	28	248
Thrust vertical, kgf	12	105
Payload, kg	15	150

The Falcon DR is a key ROV with low power requirements. It is used for simple operations like inspection and uncomplicated maintenance; it has three jaw manipulators, a wire rope cutter, a cleaning brush, a cathodic protection probe, a winch, sonar, a camera and a flashlight.

The PANTHER-XT PLUS (Figure 13) is a big powerful ROV with high-power requirements. It is launched when Falcon is not capable of doing hard work. The Seaeye Panther-XT Plus is highly suited for work tasks, including drill support, pipeline survey, salvage, cleaning, dredging and IRM to depths of 1000 meters. Air transportable Seaeye Panther-XT Plus systems are also supplied for intervention and life support tasks in support of rapid-response submarine rescue. Versatility of equipment is really high: a disc cutter, a water jet, a pipeline survey wheeled skid with boom arms and so on [10].

Figure 13. PANTHER-XT PLUS [10]

The depth rating of 1000 m is perfect for the Shtokman field with a depth of ~370 m and good for future deep-water arctic oil and gas fields.

3.5.2. ROVs Airlock

An airlock [11] design should follow the requirements;

1. It has to be solution for ROV launching and retrieving.
2. An airlock has to provide avoidance of umbilical entanglement.

First of all, we have to determine dimensions of airlock according to ROV sizes.

$$D_{airlock} = \sqrt{{W_{ROV}}^2 + {H_{ROV}}^2} \qquad (1)$$

$$Airlock\ section\ volume: V_{airlock} = \frac{\pi\, {D_{airlock}}^2}{4} L_{airlock} \qquad (2)$$

The biggest ROV we have is the Seaeye Panther-XT Plus with 2.14x1.26x1.06, as we have a lot of space in the former torpedo tubes section, let us make our airlock length $L_{airlock} = 5\ m$ because we have to put there the umbilical drum also and according to ROV dimension $D_{airlock} = \sqrt{1.26^2 + 1.06^2} = 1.64\ m$. We should make some spare space for the factor of safety and umbilical drum, so $D_{airlock} = 2.3\ m$.

$$Airlock\ section\ volume: V_{airlock} = 20.76\ m^3 \qquad (3)$$

3.5.3. ROVs studio

According to our ROVs sizes 2,14x1,1217x1,06 m and 1,035x0,635x0,6 m it was decided that whole space occupied by ROV including the gap between them will be 3,195x2,1x1,66 m. So, additionally, it is required to have clearance and space for the umbilical drum, so the ROV's studio size is 5x3,5x2 m. Thereby, $V_{studio} = 35\ m^3$

3.6. Basic assumptions

In the beginning we have to calculate basic parameters, which will help us to do design the submarine, all formulas were taken from [12]:

1. Payload volume. Usually, it is volume of all military material like torpedoes and different facilities, but here we are going to take $V_{airlock}$, V_{studio}, $V_{El\&Com}$ (volume of electronics and communications) and $V_{cargo\ storage}$. Now, we assume that the cargo storage is around 5x4x4 $V_{cargo\ storage}$ $=80m^3$. As well as cargo, let us assume that $V_{El\&Com} = 30m^3$. In such a calculation the additional margin should be included. Let us take a margin of 15%

$$V_{payload} = (V_{airlock} + V_{cargo\ storage} + V_{studio} + V_{El\&Com}) * 1.15 \qquad (4)$$

$$V_{payload} = (20.76 + 35 + 80 + 30) * 1.15 = 190.62\ m^3 \qquad (5)$$

2. Internal volume of pressure hull. Payload volume is about 30% of internal volume, so:

$$V_{prHull\ IN} = \frac{V_{payload}}{0.3} = 635.4\ m^3 \qquad (6)$$

3. External volume of pressure hull. Roughly 15% more than internal:

$$V_{prHull\,OUT} = V_{prHull\,IN} * 1.15 = 730.71\ m^3 \quad (7)$$

4. To calculate main ballast tank volume, it is required to know
   a. the reserve buoyancy ($b_{reserve}$)
   b. the utility factor ($f_{utility}$) which is responsible for residual stuff in the tanks.

   The recommended one is 0.95.

   A submarine with more reserve buoyancy has to take on more ballast before it can submerge, so we are going to make it around 0.3.

$$V_{MainBallastT} = \frac{V_{prHull\,OUT} * b_{reserve}}{f_{utility}} = 230.75\ m^3 \quad (8)$$

5. We have to find the total volume within the overall submarine envelope or "form volume". For calculation purposes the free flood volume may be allowed for by adding 15%.

   $V_{form} = (V_{MainBallastT} + V_{prHull\,OUT}) * 1.15 = 1105.68\ m^3 \quad (9)$

6. The effective power or thrust power for given speed (assumptions:

$$\vartheta_c = 10\ knots = 5.14\frac{m}{s}, K_p = 21 -$$

$$factor\ which\ is\ responsible\ for\ the\ submarine\ form:$$

$$W_{eff} = K_p * {V_{form}}^{0.64} * {\vartheta_c}^{2.9} = 214.75\ kW \quad (10)$$

7. The power required to be transmitted by the motor will be greater than the effective power by the hull efficiency, propulsor efficiency and the transmission efficiency. (For single shaft $\eta_o * \eta_H = 0.75$ and $\eta_s = 0.95$)

$$W_{motor} = \frac{W_{eff}}{\eta_o * \eta_H * \eta_s} = 301.4\ kW \quad (11)$$

8. Hotel load (domestic equipment, lighting, heating, ventilation). For the initial estimating purposes, this can be assumed to be proportional to the $V_{prHull\,OUT}$:

$$W_{hotel} = 0.075 * V_{prHull\,OUT} * 10^3 = 54.8\ kW \quad (12)$$

9. Power for stationkeeping depends of how strong the current is, so according to [12] the maximum current speed is 2.5 m/s on the surface:

$$W_{effST} = K_p * V_{form}{}^{0.64} * \vartheta_{c1}{}^{2.9} = 26.5\ kW \quad (13)$$

$$W_{motorST} = \frac{W_{eff}}{\eta_o * \eta_H * \eta_s} = 37.25\ kW \quad (14)$$

3.7. Required lifting power

It is suggested that as a test object for the lifting power calculation, we will take a 3mx3mx3m 30 tons submerged weight cube with approximate 0.2 m/s crane lifting speed. In such calculations, it is essential to include drag force and added mass. Thus, we have to assume that our added mass is half sphere under the cube.

Added mass:

$$A = \frac{2\,\pi * r^3}{3} \rho_w \quad (13)$$

Drag force:

$$F_{drag} = \frac{1}{2}\, C_D * \rho_w * L * W * \vartheta^2 \quad (14)$$

Required Power:

$$P_{lifting} = (F_{drag} + m_s * g + A * g - \rho_w * g * L * W * H) * \vartheta \quad (15)$$

Table 5. Calculation results

Name	Symbol	Value
Gravity, m/s^2	g	9,8
Drag coefficient	C_D	1,04
Submerged weight, t	m_s	30
Width of the object, m	W	3
Length of the object, m	L	3
Height of the object, m	H	3
Lifting Speed, m/s	ϑ	0,2

Added Mass, t	A	18,84
Drag Force, N	F_{drag}	193,7
Lifting Power Requirement, kW	$P_{lifting}$	62,3

3.8. Power profile

Now, when we know almost all loads, we can do an initial analysis of power requirements and select the power plant, Table 6

Table 6. Power requirements

Characteristic	Power	Transit	Positioning	Rov operates	Crane
Hotel load	54.8 kW	54,8	54,8	54,8	54,8
Propulsion	301.4 kW	301,4	-	-	-
ROV	100 kW	-	-	100	-
Crane	62.3 kW	-	-	-	62,3
Stationkeeping	37.25 kW	-	37,25	37,25	37,25
Control Systems (Assumtion)	25 kW	25	25	25	25
Total	581 kW	381,2	92,05	217,05	179,35

As you can observe from table 6, the maximum required power is during transit at full speed – 381.2 kW

First of all, it is important that the submarine should be capable of staying underwater for a long period without surfacing due to length of some operations and to ice-infested waters. Thus, diesel submarines cannot be used here because of the oxygen refill requirement, so they have to come to the surface every 30-40 hours. Nuclear submarines are not suitable due to its dangerousness, especially if they operate near to the oil and gas wells. Thereby, the submarines running on the Stirling engines, power cells or MESMA will be great options. Those are air independent propulsion systems (AIP). Air-independent propulsion is any marine propulsion technology that allows a non-nuclear submarine to operate without atmospheric oxygen. AIP can replace the diesel-electric propulsion of non-nuclear vessels. AIP is usually implemented as an auxiliary source, with the traditional diesel engine. Most such systems generate electricity which in turn drives an electric motor for propulsion or recharges the boat's batteries. The submarine's electrical system is also used for providing "hotel services": ventilation, lighting, heating and so on. Nevertheless, this consumes a small amount of power compared to that required for propulsion. AIP can be retrofitted into existing submarine hulls by inserting an additional hull compartment. AIP does not normally provide the endurance or power to replace atmospheric dependent propulsion, but allows longer submergence than a conventionally propelled submarine. A typical conventional power plant provides 3 megawatts maximum, and an AIP source around 10% of that amount. A nuclear submarine's propulsion plant is usually much greater than 20 megawatts. It is important to discuss each of those Air independent propulsion (AIP) systems [33].

Stirling engine

A stirling engine is simple and quiet, both of which are plusses for submarine use, but is large relative to its power output. Therefore, a stirling engine is not so good here as such quality as quietness is not required in civil fleet and the space it takes in engine room can't be a positive factor.

Power cells engine

The most notable use of fuel cells into submarines to date has been the development of the U212 class submarine for the Germany, the most recent of which was delivered in May 2013. The vessels boast long-distance submerged cruising thanks to an exceptional air-independent propulsion system – the key to which is a 34 kW

Siemens BZM SINAVYCIS PEM fuel cell, which has been in development with the German Navy since 1985. Siemens is continuing to improve its SINAVYCIS system, and offers a 120 kW version for larger submarines. To date this has been integrated into the HDW's U214 submarine class – a larger variant of the U212 with an advanced diving depth. Effective and compact fuel cells can be considered as a nice choice here [36].

MESMA technology

I believe that MESMA technology is ineffective and large for this project, as one ~200 kW takes around 8-10 meters space and its weight is 290-310 tons.

Decision

Mainly, it is almost impossible to make submarine working only on AIP, so there must be a diesel engine, but we should consider the case when the submarine is working only on AIP without diesel. The maximum power required to operate submarine is 381,2 kW, thus 2x ES-5700 by Bloom Energy 200kW is a nice choice as they can provide up to 2x210 kW energy (420kW) [18].

3.9. Decks number

The number of decks that can be accommodated within a pressure hull is a function of its diameter. The recognition that the distance between decks needs to be slightly larger than the height of the average man plus passing services has led to the proposition that pressure hull diameters come in unique steps [12].

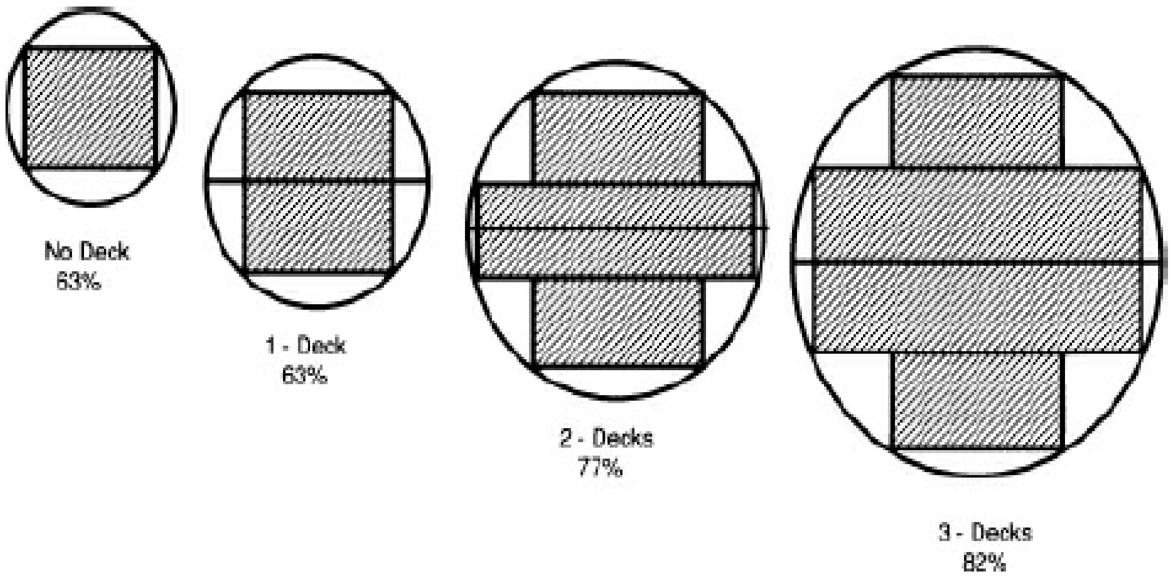

Figure 14. Utilization of hull diameter [12]

The pressure hull volume from the basic assumption section is 730 m^3 and I believe that 1 -Deck 63% is the best option as the no deck configuration requires small submarine and 2 - Decks option is for the big ones. To introduce a single through deck, the diameter needs to be slightly more than twice the height of a man, leading to the next step of something between a five and six meter diameter hull. The main deck will be at mid depth and compartments above the deck governed by the overhead curvature of the hull and compartments below the deck governed by the underneath curvature of the hull [12].

Thus, according to recommendation the 6 m diameter hull was chosen.

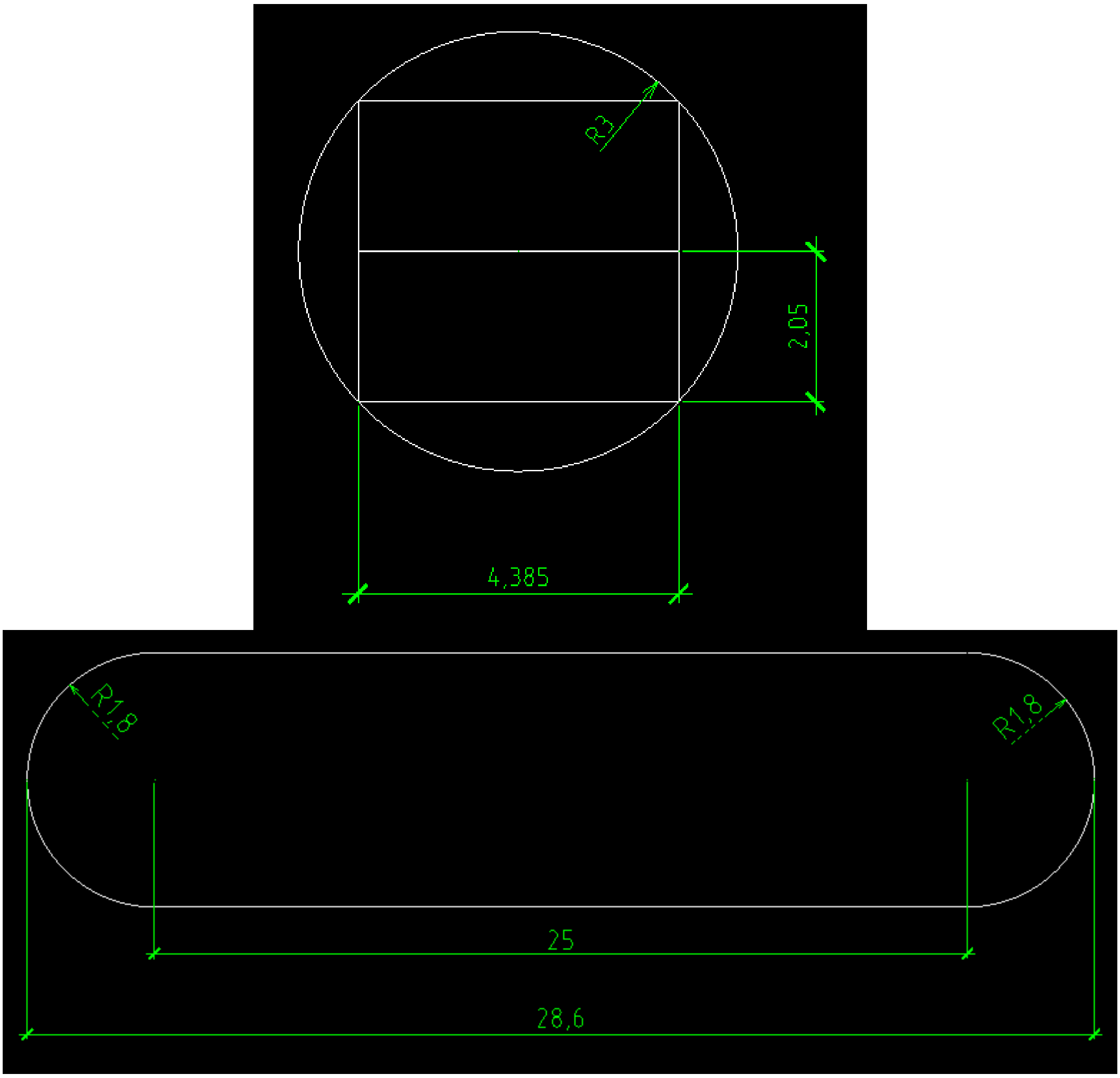

Figure 15. Pressure hull dimensions

3.10. Pumps and compressor.

3.10.1. Airlock Pump

At the time when the airlock is full with the air, the water is going to the trim tank and vice versa. As we know from the related chapter, the airlock volume is $V_{airlock} = 20.76\, m^3$. Normal air (101kPa) density is $\rho_{air} = 1.2\ \frac{kg}{m^3}$. Some of the air will leak during open/close operations, thus I suppose that 5% of air will be lost, thus it has to be refilled during surfacing.

Mainly, the pump power depends only on required air/water swapping time. To do not overload the submarine, it was decided that 30 min is optimal time. Now, I assume that we are going to use a centrifugal pump. Its efficiency is near to 80% (dry rotor) [14]. Submersion depth pressure is 2.94 MPa, water density is 1028 $\frac{kg}{m^3}$ pumping head is approximately 2 m and the volumetric flowrate is 0.0692 $\frac{m^3}{s}$

The pump power required to compress and decompress airlock can be calculated with the next equation [15]:

$$W_{airlockpump} = \frac{Q*(Hp*\rho_w g + P_s)}{1000\,\eta_{ap}} = 44.5\ kW \quad (16)$$

$$Q - volumetric\ flowrate\ \left(\frac{m^3}{s}\right);\ Hp - pumping\ head\ (m);\ \rho_w g - water\ specific\ gravity\ \left(\frac{N}{m^3}\right);\ \eta_{ap} - pump\ efficiency;\ P_s - submersion\ deph\ pressure\ (Pa)$$

Losses are small and can be neglected.

3.10.2. Trim ballast pump

The volume of trim and compensating tanks can be determined by next formula [12]:

$$V_{trimTanks} = \frac{V_{prHull\ OUT}*(\rho_{max} - \rho_{min}) + m_{stores}}{\rho_w * f_{utility}} \quad (17)$$

$$(\rho_{max} - \rho_{min}) = 10\ \frac{kg}{m^3} is\ required\ range\ of\ sea - water\ density;$$

$$m_{stores}\ is\ weight\ of\ stores, can\ be\ determined\ with:$$

$$m_{stores} = N_d * N_{crew} * C_{stores} \quad (18)$$

$$N_d -\ number\ of\ days; N_{crew} - crew\ size;$$

$$C_{stores} - daily\ stores\ consuption\ per\ person.$$

If we do not want to restock our supplies during surfacing then with a speed of 10 knots it is required 60 hours to get to the point and get back, but we should include the operation days, thus let us set it to 30 days plus transit 2.5 days.

According to [16] and [17], it was decided that $C_{stores} = 3\ kg$.

$$m_{stores} = 32.5 * 3 * 14 = 1365\ kg$$

$$V_{trimTanks} = 8.9\ m^3$$

This value is just for the expendables, but ROV and cargo should be included too

So, let us include 165 kg of ROVs and 30 t of cargo:

$$V_{trimTanksNew} = \frac{V_{prHull\,OUT} * (\rho_{max} - \rho_{min}) + m_{stores}}{\rho_w * \eta_s} = 47.26\ m^3 \qquad (19)$$

Such trim tanks must be 3:

1. Aft trim tank
2. Fore trim tank
3. Midship trim tank

It is required to compensate all moments and masses.

During the trim dive operations residual buoyancy and trim is adjusted to the values close to zero and somebody compares the actual number and the distribution of trim ballast (at trim dive) with the calculated values, later someone adjusts the values according to loading, unloading or redistribution of solid ballast operations.

All variable loads are divided into three groups:

- Variable loads that require compensate tank for the compensation (cargoes, spare parts and so on)

- Variable loads that are replaced in the same stores where they are (liquid fuel for example, ROVs, gantry crane);

- Variable loads, which are usually replaced by the trim ballast (all other variables loads).

All uncompensated mass and moments resulting from the replacement of the first two groups of loads are replaced with the help of the trim ballast tanks. During the compensation of cargoes, it is recommended to follow basic principles:

1. During the ROV and gantry crane operations, the compensation has to be done immediately.
2. During the long trip food, water and similar kind of staff spend evenly and the compensation carries out along with the fuel consumption [20].

To counterbalance the submarine fast, the volumetric flowrate must be high enough, for the 30 sec, it is 0.3 $\frac{m^3}{s}$. The pumps efficiency for lower power values is less than 0.8, let us take 0.65. Thus, the required pump power is:

$$W_{trimpump} = \frac{Q*H*\rho_w g}{1000\,\eta_{tp}} = 48.8\ kW \qquad (20)$$

3.10.3. Compressor for the main ballast

As it is well known, a submarine requires a compressor to store air in an air tank for the surfacing purpose. The air volume is equal to the volume of the main ballast tank, but to reduce that air amount to 17 m^3, the air must be compressed. So, with help of [19], we know that 35 kW compressor is necessary. Also, 17 m^3 will be installed above the pressure hull.

The power requirements of compressors and pumps are not so high. Usually, they are used during ROV, crane and station keeping phases. Thus, the whole 420 kW limit is not reached anyway, so with maximum speed of 10 knots it is enough to use only fuel cells and early assumption about diesel requirement is not right.

3.11. Fuel tank

According to all calculations, the energy required for 2.5 days of transit:

$$A_{transit} = 381\ kW * 2.5 * 24 = 22860\ kW * hr \qquad (21)$$

For the rest of the operation time, we can assume, based on table 6 and chapter 4.9, that 200 kW per hour average must be more than enough, thus the energy requirements for the rest of the mission can be calculated:

$$A_{rest} = 200\ kW * 30 * 24 = 144000\ kW * hr \qquad (22)$$

$$A_{mission} = 144000 + 22860 = 166860\ kW * hr \qquad (23)$$

Our ES-5700 by Bloom Energy fuel cells are running on the natural gas [18], it is inconvenient to use big fuel tanks though, thus it is suggested with the help of [21], [22] and [23] to use compressed natural gas or CNG.

One gallon of gasoline equivalent contains 114000 BTUs or 33.41 $kW * hr$ and requires 0.51 cubic feet or 0.0144 cubic meter of space in a CNG tank.

$$V_{CNG} = \frac{166860}{33.41} * 0.0144 = 72\ m^3 \qquad (24)$$

Now we are going to add 15% margin for the tank volume and emergencies.

$$V_{fuelTank} = 72 * 1.15 = 82.8\ m^3 = 83\ m^3 \quad (25)$$

Usually, CNG is stored in hard containers at a pressure of 20–25 MPa (2.900–3.600 psi), usually in cylindrical or spherical shapes. [24]

3.12. Pressure and outer hulls section

3.12.1. Wall thickness

So, with knowledge of the maximum submersion depth with the von Mises yield criterion:

$$\sigma_{vM} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1 * \sigma_2 - \sigma_1 * \sigma_3 - \sigma_2 * \sigma_3} \quad (26)$$

Diameter of the hull>>wall thickness, thus we can use this equation. The principal stress for a cylinder:

$$\sigma_1 = \sigma_r = 0; \sigma_2 = \sigma_t = -P * \frac{rh}{h}; \sigma_3 = \sigma_z = -P * \frac{rh}{2h} \quad (27)$$

When h/r>0 we can use this formulas. Let us put (27) in (26):

$$\sigma_{vM} = \frac{rh\sqrt{3}}{2h} * P; \quad (28)$$

Finally, we can get the equation for the wall thickness:

$$h = \frac{rh\sqrt{3}}{2\sigma_{vM}} * P \quad (29)$$

$$\sigma_y = \eta_{saf}\sigma_{vM}; \ (30)$$

The calculation result for HY-130 (well-known steel and something average between HY-116 and HY-156):

Table 7. Results of the wall thickness calculations

Parameter	Symbol	Value
Operating pressure	P	2.94 Mpa
Safety coefficient	η_{saf}	2
Yield Strength	σ_y	900 Mpa
Hull radius	rh	9.1 m
Hull thickness(safety margin included)	h	52 mm

Now, we know the required wall thickness with present materials approximately.

3.12.2. Hulls dimensions

There are several types of submarine dimensions:

- H_{oh} – outer hull height;

- H_{sub} – submarine height;
- H_{fb} – freeboard height;
- H_{wl} – tailplanes height;
- H_{wlfb} – distance between higher part of a submarine and waterline;
- L_{ph} – pressure hull length;
- L_{wl} – waterline length;
- L_{max} – submarine length;
- B_{max} – submarine width (beam);
- B_{wl} – waterline width;
- D_{ph} – pressure hull diameter;
- T_{wl} – distance between lower flat submarine part and waterline;
- WL – waterline; [20]

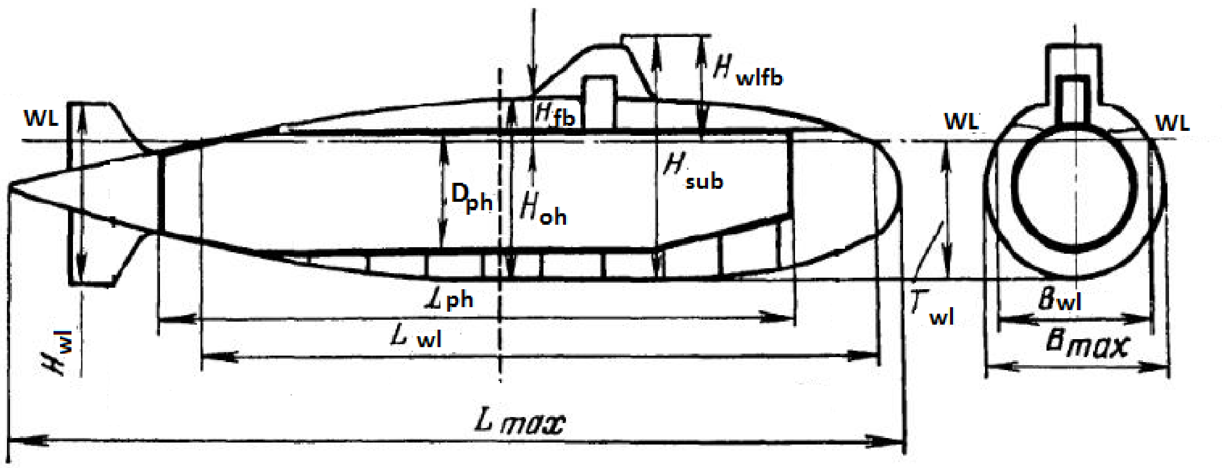

Figure 16. Hull parameters. [20]

According to results from chapters 3.6 and 3.9, our dimesions can be easily evaluated.

Table 8. Hull dimensions

Paremeter	Values, m
L_{max}	50

B_{max}	7
H_{sub}	8,8
H_{oh}	7,1
H_{fb}	0,8
H_{wl}	8,2
H_{wlfb}	2,5
B_{wl}	5,8
L_{ph}	28,6
D_{ph}	6
L_{wl}	35
T_{wl}	6,3

The main ballast tanks are made in a moonlike shape with the length of 16 meters and spread across the pressure hull from the both sides.

Regarding to the trim tanks, it is described in the next chapter.

3.12.3. Hull modeling

Now, when we know all dimensions and place of all components, it is possible to visualize the submarine with help of 3ds Max, Figure 17.

Figure 17. Pressure hull with ballast tanks and water tank for airlock

Red ones are the ballast tanks, blue one is the water tank. All dimensions are according to calculations.

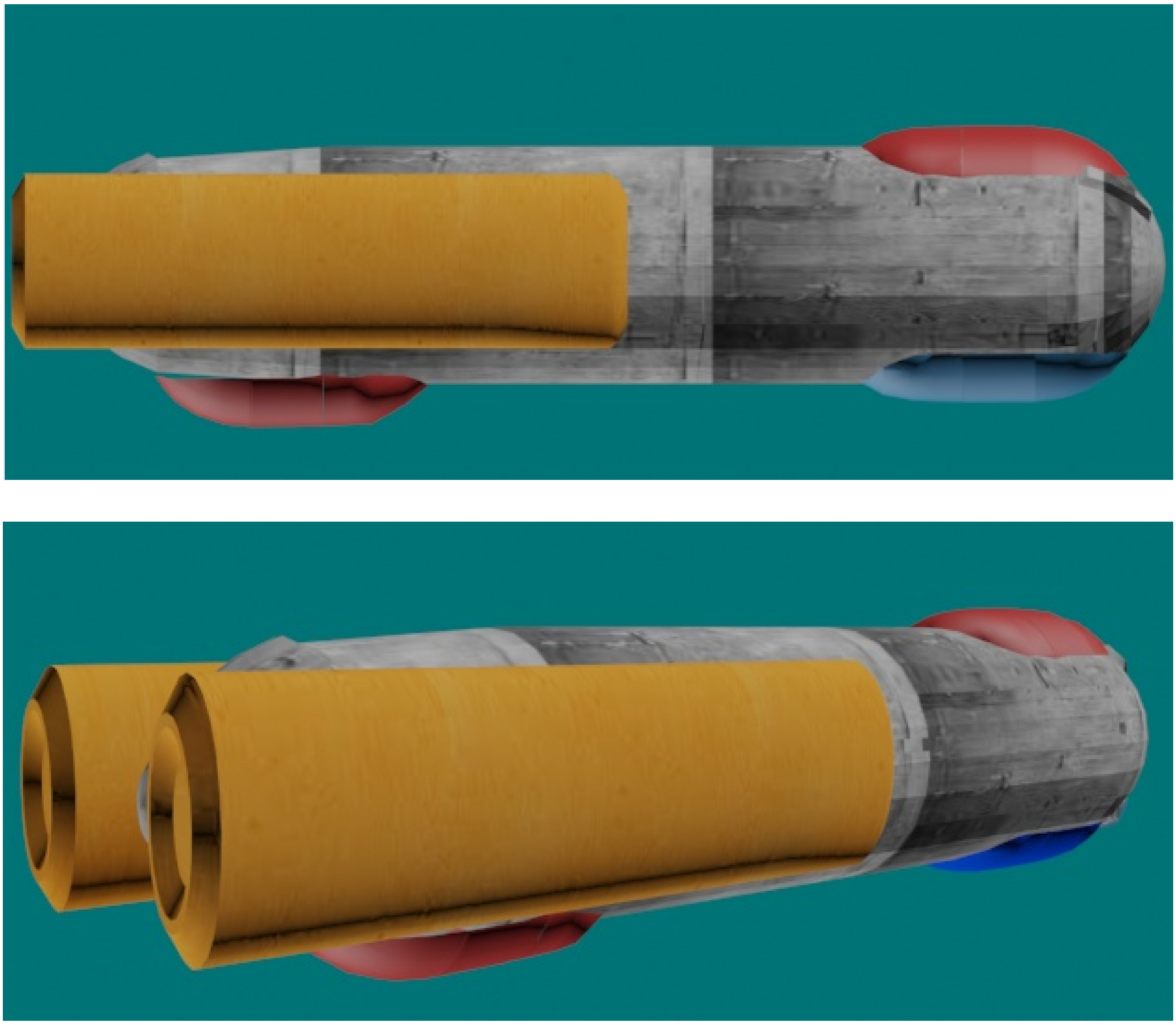

Figure 18. Pressure hull with the ballast tanks

Figure 18 shows the pressure hull with ballast tank divided into 2 parts working with help of the compressor from chapter 4.9.3 and with the volume from chapter 4.5.

The airlock water tank is under the section with ROVs, the fore trim tank is here also but it is situated above. According to chapter 4.9.2, the whole volume of trim tanks must be around 50 m^3, but we have to compensate the fuel tank also, it weighs 16,6 tones, thus with help of the equation (19) we know that our tank has to be 17 m^3. So the middle tank is 17 m^3 and the fore is 50/2 = 25 m^3 as we require second one in the aft part of the submarine.

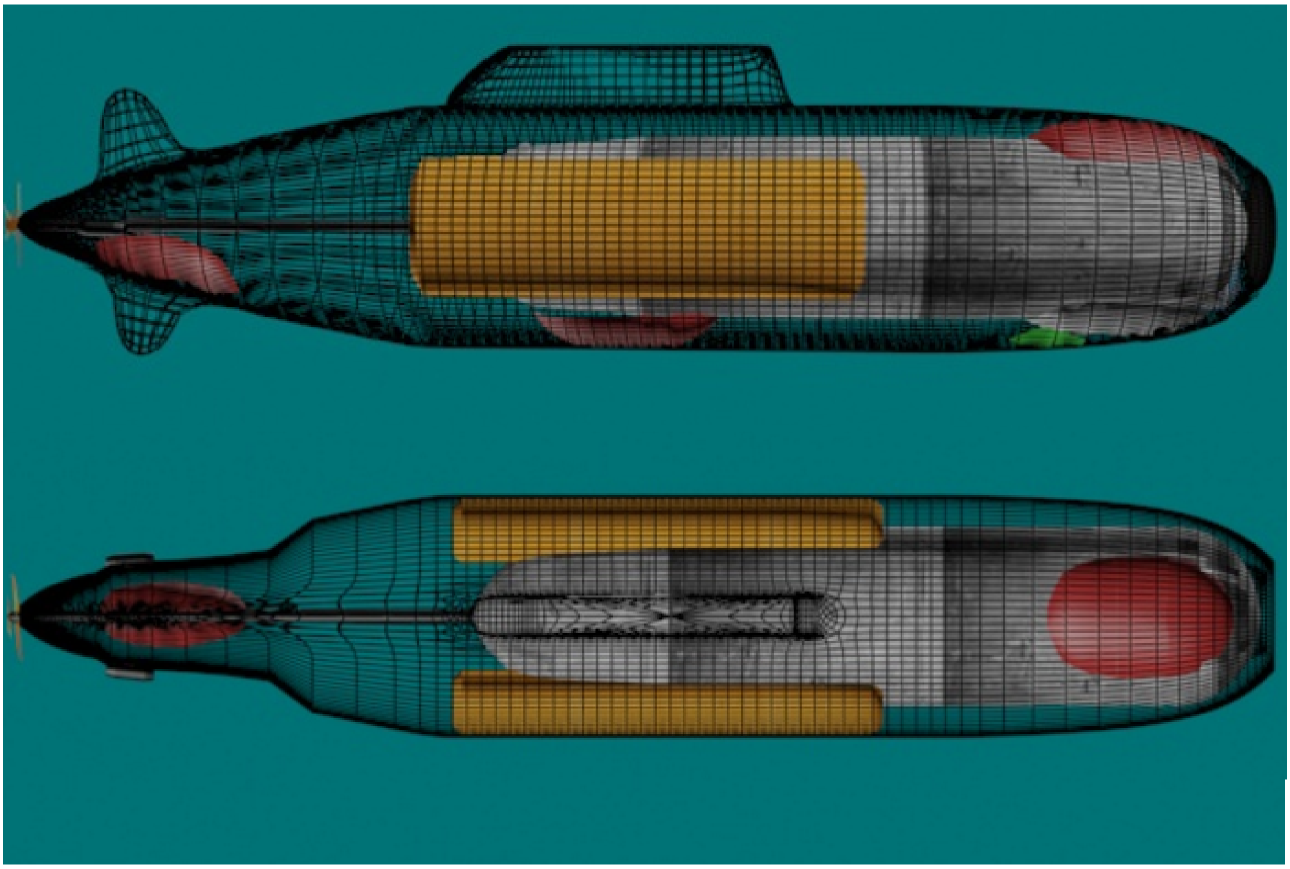

Figure 19. Whole submarine according to calculation results (without fuel tanks)

Figure 19 shows whole body of the submarine with 3 trim tanks (25 m^3, 17 m^3, 25 m^3), with ballast tanks and airlock water tank. The fuel tank is located along the shaft and attached to aft trim tank.

3.13. Internal arrangements

Usually, when somebody wants to show the disposition of all internal pressure hull volume, he uses a Flounder diagram (see Figure 20). The outer boundary of this diagram is a curve of cross-sectional areas of the pressure hull to a base of length, which represents the longitudinal disposition of available volume. Space demands can be indicated as individual areas in the diagram together with their longitudinal and vertical location demonstration how the available internal space has been used up [12].

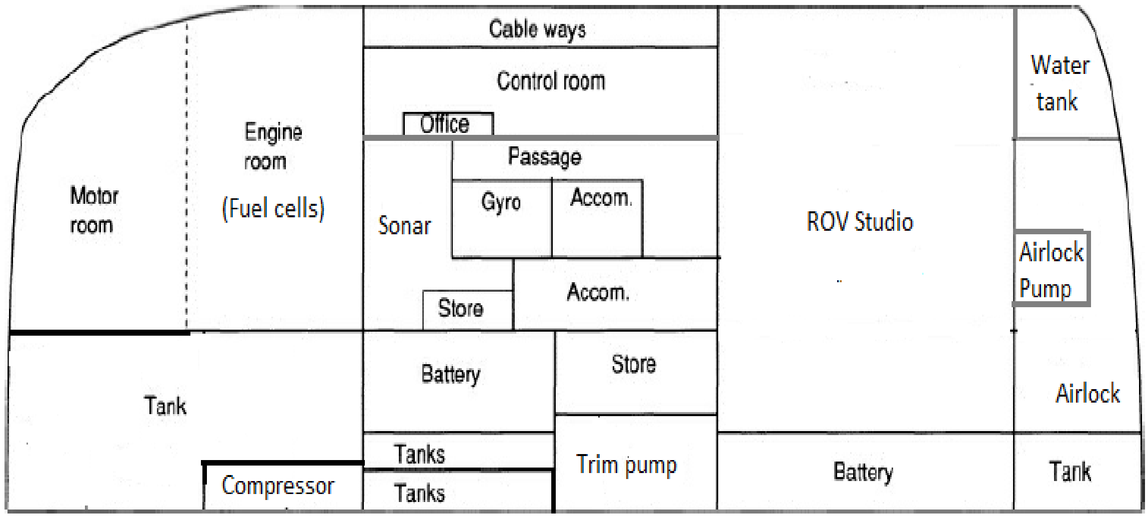

Figure 20. Flounder diagram of the pressure hull and tanks around

Another way to represent the submarine is a whole picture. Figure 21:

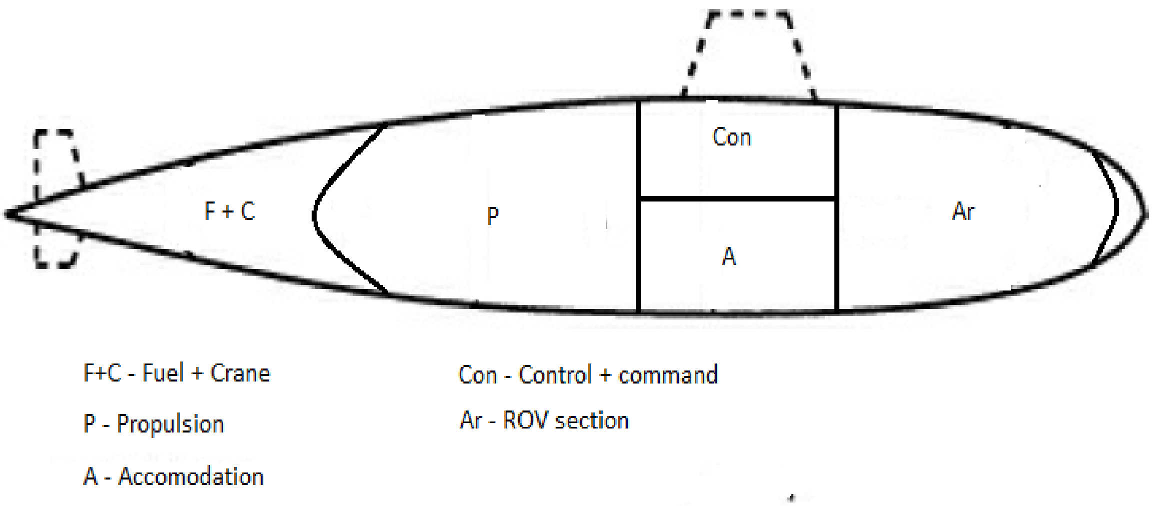

Figure 21. Arrangement

Control and command rooms are located in the top of pressure hull near the sail. It is common in submarine design and there is no need to change something here. The difference is only in computers and equipment inside. Usually, a control room is divided into navigational and machinery control rooms. All equipment requires (gyroscope, accelerometers, computers and so on) up to 10 kW energy in the high time.

The accommodation section is under the control and command rooms. It is very convenient location. It helps to get to all parts of the submarine in a short time. Three common bed rooms with four beds each, two single small rooms for a captain and a mate. One medium-size common room is for relaxation with any kind of stuff (TV, small gym and so on).

The ROV section includes the place for ROV storage, maintenance and control. In addition, airlock section is next to this part of the vessel.

The fuel tanks are located in the back of the submarine and have direct connection with the fuel cells, which in turn can distribute energy between batteries by the cable ways or transmit it to any section of the submarine, including motor room, command room and so on.

The propulsion section is behind the engine room with the fuel cells and motor room where electric energy goes through transformation into the mechanical energy of the screw through the shaft.

3.14. Building possibility in Russia

The main submarine building location in Russia is Severodvinsk. So, let us name the list of things that can be manufactured in Russian Federation:

1. Pressure hull and outer hull
2. Ballast and trim tanks
3. Shaft
4. Screw
5. Computers

6. Sonar and gyroscope
7. Cable ways

Thing that cannot be built in Russian Federation:

1. Fuel cells
2. ROV
3. CNG tank

First of all, it is very important to understand that Russia has a huge experience in submarines building. It takes 3-5 years to create a new vessel from scratch. Main problem is only in HY-130 steel as there are no factories to produce such material. It can be substituted by АБ-2 steel. We can order it from “Stal’ invest” (Cherepovec). Rests of the things are very typical for submarine and may be built without imports.

As for the fuel, there are many CNG tanks producer like “Rugasco”, “Digitronics” and so on, but they manufacture small-volume balloons. There are two options:

a. Make conditions for huge balloon production.
b. Import required tanks (“John Wood”, USA).

Fuel cells cannot be built in Russia in the foreseeable future. Thus, we can only import from Bloom energy or Siemence companies.

As for ROV, there is only one ROV manufacture in Russian Federation. This company is well-known as “GNOM”. It is small company, and they do not produce high-class ROV. Their products can be used only for monitoring. This is unsuitable for us, so our options are Seaeye or Oceeniring companies that have huge ROV building experience. The choice of those machines is truly amazing.

Regards to the cost of the submarine, it is diffucult to say something because the price of submarine manufacturing is private information. We have found only that 73 long submarine costs 300 mln. $ [37]. At the same time, the price of a ROV support vessel is around 20 mln. $ [38], but the problem here is that we cannot just operate with such ship, but require additional fleet. The risks here are much more higher.

4. Modeling of surfacing

4.1. Basics

4.1.1. Surfacing

It is well known that a submarine can crack ice with thickness of 1 meter, but the captain of the vessel should know what the capacity of ice layer above when it comes to surfacing. A submarine can measure the thickness of ice in many ways. One of them is when an ice-profiling sonar sends out ping that travels through the water to the ice above, bounces off the ice, and returns to the sensor [30]. We then measure the time it takes for a ping to travel to the ice and back. If we know the speed of sound in the water, if we know the density of the water, if we know the pointing direction of the sonar, and if we know how much water is above our sensor, then we can estimate the thickness of the ice. [30].

Another way is an air gun that sends big bubble of air to the surface with the capability of cracking the ice with certain thickness. If such event happens, the submarine will safely proceed to surfacing, if not the captain should order to change the location and repeat the process.

Usually, submarines do not surface through the ices if there are no needs like ice material testing or emergencies.

Today, submarines surface from under the ice by creating positive buoyancy force in a way of extracting water from ballasting tanks. This produces static loading of the ice cover from below and allows the submarine to break through the frozen layer.

Nevertheless, this method could cause inevitable damage to the cabin, stern rudders, external hull and upper deck. Additionally, the destruction of the ice layer through static loading may result in losing stability, thus overturning a submarine.

An experiment of the Russian Academy of science shows that a common 100 meters long submarine with an elongation of 1:8—can break an ice plate only when traveling very close to the ice-water interface. Thus, in order to break an ice sheet up to 1 meter thick, the submarine has to move at a depth of no more than around 30 meters, measured from the axis of the submarine's body to the water-ice interface.

The destruction of ice layer up to 2 meters thick is possible if the submarine sails at a depth of no more than 25 meters, but the destruction of ice cover 3 meters thick is impossible, according to theoretical results [31].

4.1.2. Ice behavior

The main idea is that the highest stresses affect the sail of the submarine during the sail-ice interaction, and a hull does not have so many problems with that.

The sail and hull should be designed for an average ice thickness of 1 meter in the Barents region. The failure of a material is usually classified into brittle failure (fracture) or ductile failure (yield). Depending on the conditions (such as loading rate temperature) majority of materials can fail in a ductile or brittle ductile manner. Nevertheless, for practical situations, materials can be classified as either brittle or ductile [25]. We can consider ice as a brittle material, therefore, next assumptions should be right [26]:

1. Relatively little plastic deformation is observed.
2. Crack propagates almost perpendicular to the direction of applied stress.
3. Crack is very unstable: propagates fast without an increase in applied stress.
4. Low energy absorption before fracture.

It is suggested to take September as a month for this project. Therefore, according to figure 5 ice thickness here is 1 m and the temperature is around -10 °C. Such processes are not so easy to calculate, thus, it was decided to use ANSYS – an American computer software for engineering with finite-element analysis, structural analysis and computational fluid dynamics. The hull material properties were taken for steel HY-130, and the calculated wall thickness were applied [25], [26].

4.2. Modeling

First of all, it was decided to simplify the problem and check only capability of HY-130 material with a given wall thickness, so a simple form of the submarine was taken and the ice surface is a solid plate with 1 meter thickness. (See Figure 22)

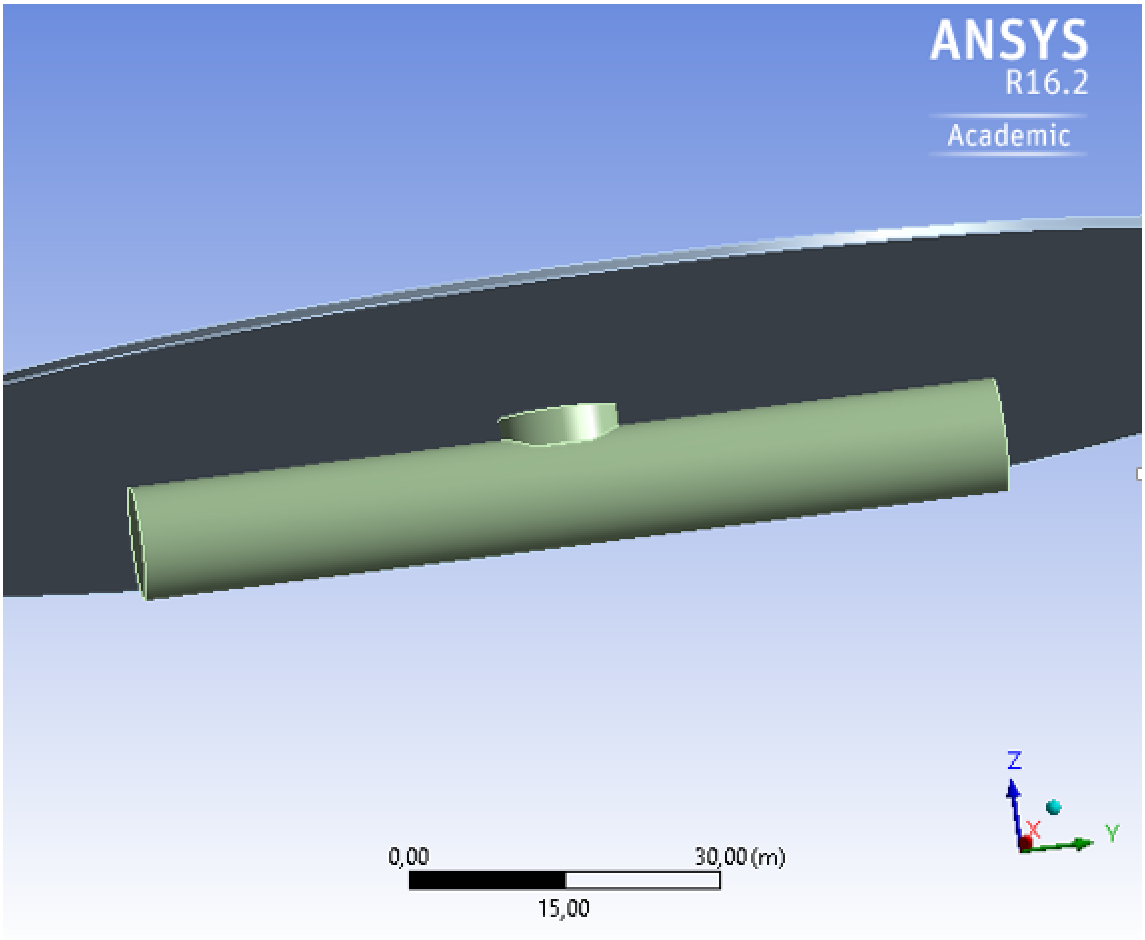

Figure 22. Initial conditions

HY-130 is a quenched and tempered low-carbon alloy steel that has application as material for pressure vessels, heavy construction equipment and in large steel structures. It has high-tensile strength (ultimate and yield), very good ductility, weld ability, notch toughness and atmospheric corrosion resistance (See Table 9).

Table 9. HY-130 characteristics

Parameter	Value
Density	7850, kg m^-3
Coefficient of Thermal Expansion	1,2e-005 C^-1
Specific Heat	434, J kg^-1 C^-1
Thermal Conductivity	60,5 W m^-1 C^-1
Resistivity	1,7e-007 ohm m
Compressive Yield Strength	2,5e+008 Pa
Tensile Yield Strength	2,5e+008 Pa
Tensile Ultimate Strength	4,6e+008 Pa
Young's Modulus	2,e+011 Pa
Poisson's Ratio	0,3
Bulk Modulus	1,6667e+011 Pa
Shear Modulus	7,6923e+010

Ice parameters are typical for Barents Sea, the modeling is for the -10 °C, Tables 10 and 11.

Table 10. Ice parameters – 1

Density kg m^-3	Thermal Conductivity W m^-1 C^-1	Temperature C
919,4	2,39	-20,
919,4	2,34	-15,
919,	2,3	-10,
917,	2,25	-5,

Table 11. Ice parameters – 2

Parameter	Value
Tensile Ultimate Strength	1,2e+006 Pa
Young's Modulus	5,e+009
Poisson's Ratio	0,33
Bulk Modulus	4,902e+009 Pa
Shear Modulus	1,8797e+009 Pa

The Drucker-Prager strength linear criterion was taken for the ice. It is pressure dependent model for investigation, whether a material undergoes plastic yielding or has failed. Usually, it is common criteria for rock, foams, concrete, polymers and other pressure-dependent materials. The main reason for our choice is that this criterion does not require a huge amount of data like Johnson-Holmquist criteria, which we do not possess.

4.3. Results and conclusion

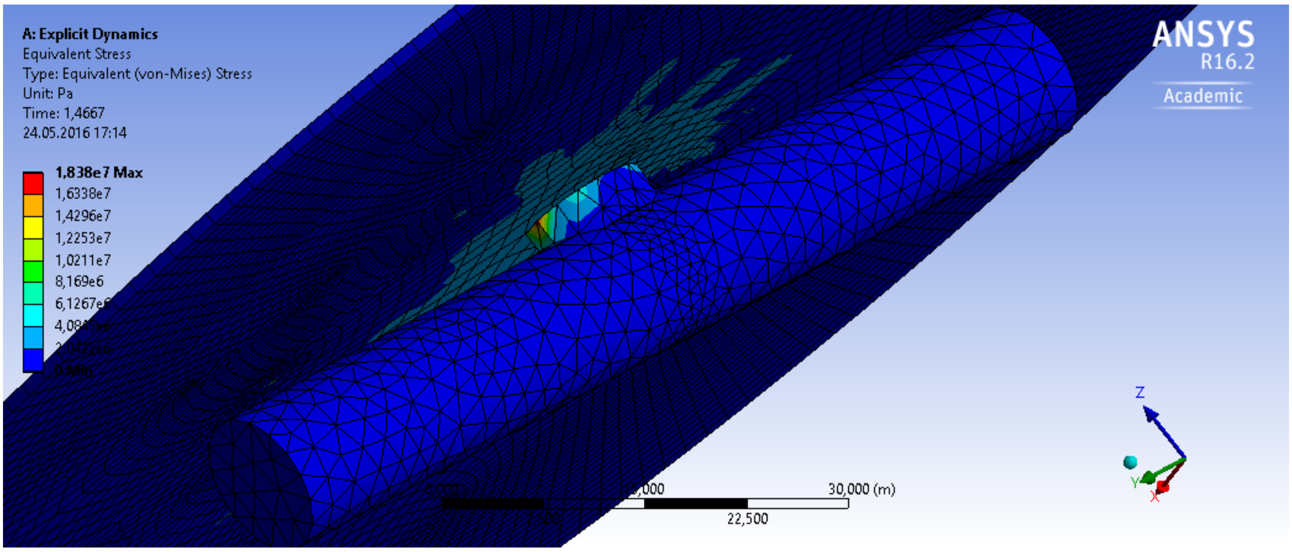

Figure 23. Cracking moment

The submarine is moving with the speed of 0.5 m/s. At the moment of the cracking, stresses can be observed from Figure 23. As it was anticipated, the main stresses affect the sail, the asset value is far less than material can withstand without deformation. So, HY-130 with 52 mm wall thickness is suitable for cracking 1 meter ice layer.

5. Risk assessment

First of all, we must identify all the risks and make risk matrices to see what hazards are dangerous, see Tables 12 and 11.

Some part of risks are taken from the same assessment as for a ship. Like collision with jetty, but the core belongs only to submarine as it is more dangerous to get stuck inside the "iron capsule" 300 meters below the sea than on the surface. Nevertheless, ships face all weather surprises like wind, snow, waves, rain and ice.

Table 12. Description of risks

Designation	Hazard	Probability	Severity rank			
			Asset	Reputation	Lives	Environment
R1	Collision with jetty (without leak)	4	1	-	-	-
R2	Collision with jetty (with leak)	1	3	-	3	2
R3	Fuel cells failure	2	3	2	3	-
R4	Grounding (withoutleak)	2	-	-	2	-
R5	Grounding (withleak)	1	3	-	2	2
R6	Gantry crane failure	2	3	1	-	-
R7	Breakdown of a submarine (with immediate response)	3	2	-	3	-
R8	Breakdown of a submarine (with slow response)	2	4	-	4	-
R9	Health problem of a person	-	1	-	4	-
R10	Navigation system failure	2	2	1	-	-
R11	Outer hull destruction during	2	4	-	3	-

	the surfacing in the ice					
R12	Exceeding the maximum submersion depth	3	3	-	3	-
R13	Screw destruction	2	1	-	-	-
R14	Collision with an unknown object(small)	1	-	-	2	-
R15	Collision with an unknown object(big)	1	3	-	3	3
			1 - minor, 2 - major, 3 - critical, 4 - catastrophic			

Table 13. Risk matrices[27],[28]

	Asset				
Probability	5				
	4	R1			
	3		R7	R12	
	2	R13	R10	R3 R6	R8 R11
	1	R14		R2 R5	
		1	2	3	4
		Severity			

	Reputation				
Probability	5				
	4				
	3				
	2	R6 R10	R3		
	1				
		1	2	3	4
		Severity			

	Lives				
Probability	5				
	4				
	3			R7 R12	R9
	2			R3 R11	R4 R8
	1		R5 R14	R2 R15	
		1	2	3	4
		Severity			

	Environment				
Probability	5				
	4				
	3				
	2				
	1		R2 R5	R15	
		1	2	3	4
		Severity			

(red)	Unacceptable risk
(yellow)	Acceptable risk
(blue)	Negligible risk

As we can observe, all the risks are acceptable or negligible. Thus, such technology can be considered as safe, but risks designates R8 (Breakdown of a submarine (with a slow response)), R9 (Health problem of a person), R11 (Outer hull destruction during the surfacing in the ice), R12 (Exceeding the maximum submersion depth) are not far from the danger zone.

- R8 can be reduced by good emergency training and by modern alarm system installation;
- R9 can be dangerous in the case of improper choice of the crewmembers;
- R11 is riskily when the sonar system is broken or ice layer thickness determination goes wrong (need to check equipment twice and choose qualified staff);
- R12 is fully dependent on the computers and staff experience.

Conclusions

This work provides basic submarine theory and shows the possible design of a submarine as a mothership for ROVs to help in a field development processes. Such a submarine can operate in ice-infested waters of the Russian Arctic shelf. Based on the obtained results, the following conclusions are made:

- It is technically possible to use such technology as a support field development facility for the Russia part of the Arctic shelf and especially for the Shtokman gascondensate field and in the Kara Sea.
- The design process was taken from the military industry, thus a lot of things inside the submarine are the same.
- A slow speed submarine (10 knots) can rely just on air-independent propulsion with the total power of 420 kW.
- It is sufficient with a 50 meters long submarine with 7 meters beam to use this technology for field development.
- HY-130 steel with 52 mm wall thickness can be used for surfacing through the ice with thickness of 1 meter and such ice layers are typical for the Russian Arctic zones of oil and gas.
- It is unreal to build this submarine in Russia without import of the CNG tank and fuel cells.
- The risks are acceptable.

Nevertheless, there things that should be added to this project in order to prove its viability completely:

- It would be very tought for me to assess the cost of this project due to the privacy of information concerning the construction of real military submarines. Prices of different materials at various places, computers, safety submarine systems and so on are enigmas for me. Thus, this project requires a full economic assessment.
- During the crane operations, the submarine requires proper equilibrium polygon analysis; the calculated trim tanks should be enough though.

- The submarine needs real resistance calculation during transit, that will change power requirements, but the values will not change so much. If it changes drastically, this problem can be solved just by adding one additional block of fuel cells. Dimensions of the block are not so big, so there is enough space for the third one.

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APPENDIX 1. Bloom energy data sheet.

PRODUCT DATASHEET

Bloomenergy

ES-5700

Clean, Reliable, Affordable Energy

CLEAN, RELIABLE POWER ON DEMAND

Bloom Energy's ES-5700 delivers clean power that reduces emissions and energy costs. The modular architecture enables the installation to be tailored to the actual electricity demand, with a flexibility to add servers as the load increases. The ES-5700 actively communicates with Bloom Energy's network operations centers so system performance can be monitored and maintained 24 hours per day, 365 days per year.

INNOVATIVE TECHNOLOGY

Utilizing patented solid oxide fuel cell (SOFC) technology, the ES-5700 produces combustion-free power at unprecedented efficiencies, meaning it consumes less fuel and produces less CO_2 than competing technologies. Additionally, no water is needed under normal operating conditions.

ALL-ELECTRIC POWER

The ES-5700, which operates at a very high electrical efficiency, eliminates the need for complicated and costly CHP systems. Combining the standard electrical and fuel connections along with compact footprint and sleek design, the ES-5700 is the most deployable fuel cell on the market.

CONTROLLED AND PREDICTABLE COST

By providing efficient on-site power generation, the economic and environmental benefits are central to the ES-5700 value proposition. Bloom Energy customers can lock in their long term energy costs and mitigate the risk of electricity rate increases. The ES-5700 has been designed in compliance with a variety of safety standards and is backed by a comprehensive warranty.

About Bloom Energy

Bloom Energy is making clean, reliable energy affordable. Our unique on-site power generation systems utilize an innovative fuel cell technology with roots in NASA's Mars program. By leveraging breakthrough advances in materials science, Bloom Energy systems are among the most efficient energy generators, providing for significantly reduced operating costs and dramatically lower greenhouse gas emissions. Bloom Energy Servers are currently producing power for many Fortune 500 companies including Apple, Google, Walmart, AT&T, eBay, Staples, as well as notable non-profit organizations such as Caltech and Kaiser Permanente.

Headquarters:
Sunnyvale, California

For More Information:
www.bloomenergy.com

ES-5700

Technical Highlights	
Outputs	
Nameplate power output (net AC)	210 kW
Base load output (net AC)	200 kW
Electrical connection	480 V, 3-phase, 60 Hz
Inputs	
Fuels	Natural gas, directed biogas
Input fuel pressure	15 psig
Water	None during normal operation
Efficiency	
Cumulative electrical efficiency (LHV net AC)	52-60%
Heat rate (HHV)	6,295-7,264 Btu/kWh
Emissions	
NOx	< 0.01 lbs/MWh
SOx	Negligible
CO	< 0.10 lbs/MWh
VOCs	< 0.02 lbs/MWh
CO_2 @ stated efficiency	735-849 lbs/MWh on natural gas; carbon neutral on directed biogas
Physical Attributes and Environment	
Weight	19.4 tons
Dimensions	26' 5" x 8' 7" x 6' 9"
Temperature range	-20° to 45° C
Humidity	0% - 100%
Seismic vibration	IBC site class D
Location	Outdoor
Noise	< 70 dBA @ 6 feet
Codes and Standards	
Complies with Rule 21 interconnection and IEEE1547 standards	
Exempt from CA Air District permitting; meets stringent CARB 2007 emissions standards	
Product listed by Underwriters Laboratories Inc. (UL) to ANSI/CSA America FC 1-2004	
Additional Notes	
Access to a secure website to monitor system performance & environmental benefits	
Remotely managed and monitored by Bloom Energy	
Capable of emergency stop based on input from the site	

Bloomenergy

Bloom Energy Corporation
1299 Orleans Drive
Sunnyvale CA 94089
T 408 543 1500
www.bloomenergy.com

APPENDIX 2. ANSYS data.

Units

TABLE 1

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (A4)

Geometry

TABLE 2
Model (A4) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	C:\Учеба кароч\Ansys\Proj_files\dp0\SYS\DM\SYS.agdb
Type	DesignModeler
Length Unit	Meters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	175,17 m
Length Y	175,17 m
Length Z	4,5 m

Properties	
Volume	24630 m³
Mass	2,6263e+007 kg
Scale Factor Value	1,
Statistics	
Bodies	2
Active Bodies	2
Nodes	36580
Elements	18235
Mesh Metric	None
Basic Geometry Options	
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	No
Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\леново\AppData\Local\Temp
Analysis Type	3-D

Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

TABLE 3
Model (A4) > Geometry > Parts

Object Name	*Solid*	*Solid*
State	Meshed	
Graphics Properties		
Visible	Yes	
Transparency	1	
Definition		
Suppressed	No	
Stiffness Behavior	Rigid	Flexible
Reference Temperature	By Environment	
Reference Frame	Lagrangian	
Coordinate System		Default Coordinate System
Material		
Assignment	Structural Steel	Ice
Nonlinear Effects		Yes
Thermal Strain Effects		Yes
Bounding Box		
Length X	12,875 m	175,17 m
Length Y	15,473 m	175,17 m
Length Z	3,5 m	1, m
Properties		
Volume	530,36 m³	24100 m³
Mass	4,1633e+006 kg	2,2099e+007 kg

Centroid X	-6,0608e-005 m	-1,8644e-015 m
Centroid Y	-1,0023e-004 m	-2,4061e-015 m
Centroid Z	-1,75 m	0,5 m
Moment of Inertia Ip1	7,2569e+007 kg·m²	4,2263e+010 kg·m²
Moment of Inertia Ip2	4,0486e+007 kg·m²	4,2263e+010 kg·m²
Moment of Inertia Ip3	1,0459e+008 kg·m²	8,4523e+010 kg·m²
Statistics		
Nodes	592	35988
Elements	399	17836
Mesh Metric	None	

Coordinate Systems

TABLE 4
Model (A4) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0,
Origin	
Origin X	0, m
Origin Y	0, m
Origin Z	0, m
Directional Vectors	
X Axis Data	[1, 0, 0,]
Y Axis Data	[0, 1, 0,]
Z Axis Data	[0, 0, 1,]

Connections

TABLE 5
Model (A4) > Connections

Object Name	*Connections*
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

TABLE 6
Model (A4) > Connections > Body Interactions

Object Name	*Body Interactions*
State	Fully Defined
Advanced	
Contact Detection	Trajectory
Formulation	Penalty
Body Self Contact	Program Controlled
Element Self Contact	Program Controlled
Tolerance	0,2

TABLE 7
Model (A4) > Connections > Body Interactions > Body Interaction

Object Name	*Body Interaction*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Frictionless
Suppressed	No

Mesh

TABLE 8
Model (A4) > Mesh

Object Name	*Mesh*
State	Solved
Display	
Display Style	Body Color
Defaults	
Physics Preference	Explicit
Relevance	0
Sizing	
Use Advanced Size Function	Off
Relevance Center	Medium
Element Size	1,50 m
Initial Size Seed	Active Assembly
Smoothing	High
Transition	Slow
Span Angle Center	Coarse
Minimum Edge Length	44,4480 m
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0,272
Maximum Layers	5
Growth Rate	1,2
Inflation Algorithm	Pre

View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Patch Independent Options	
Topology Checking	No
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Shape Checking	Explicit
Element Midside Nodes	Dropped
Straight Sided Elements	
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Full Mesh
Rigid Face Mesh Type	Quad/Tri
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default
Statistics	
Nodes	36580
Elements	18235
Mesh Metric	None

TABLE 9
Model (A4) > Fracture

Object Name	*Fracture*
State	Solved

Named Selections

TABLE 10
Model (A4) > Named Selections > Named Selections

Object Name	*Selection*	*Select*
State	Fully Defined	
Scope		
Scoping Method	Geometry Selection	
Geometry	1 Body	
Definition		
Send to Solver	Yes	
Visible	Yes	
Program Controlled Inflation	Exclude	
Statistics		
Type	Manual	
Total Selection	1 Body	
Suppressed	0	
Used by Mesh Worksheet	No	

Explicit Dynamics (A5)

TABLE 11
Model (A4) > Analysis

Object Name	*Explicit Dynamics (A5)*
State	Solved
Definition	
Physics Type	Structural
Analysis Type	Explicit Dynamics

Solver Target	AUTODYN
Options	
Environment Temperature	-10, °C
Generate Input Only	No

TABLE 12
Model (A4) > Explicit Dynamics (A5) > Initial Conditions

Object Name	*Initial Conditions*
State	Fully Defined

TABLE 13
Model (A4) > Explicit Dynamics (A5) > Initial Conditions > Initial Condition

Object Name	*Pre-Stress (None)*
State	Fully Defined
Definition	
Pre-Stress Environment	None
Pressure Initialization	From Deformed State

TABLE 14
Model (A4) > Explicit Dynamics (A5) > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Analysis Settings Preference	
Type	Program Controlled
Step Controls	
Resume From Cycle	0
Maximum Number of Cycles	1e+07
End Time	2,3 s
Maximum Energy Error	20,
Reference Energy Cycle	0

Initial Time Step	Program Controlled
Minimum Time Step	Program Controlled
Maximum Time Step	Program Controlled
Time Step Safety Factor	0,9
Characteristic Dimension	Diagonals
Automatic Mass Scaling	No
Solver Controls	
Solve Units	mm, mg, ms
Beam Solution Type	Bending
Beam Time Step Safety Factor	0,5
Hex Integration Type	Exact
Shell Sublayers	3
Shell Shear Correction Factor	0,8333
Shell BWC Warp Correction	Yes
Shell Thickness Update	Nodal
Tet Integration	Average Nodal Pressure
Shell Inertia Update	Recompute
Density Update	Program Controlled
Minimum Velocity	1,e-006 m s^-1
Maximum Velocity	1,e+010 m s^-1
Radius Cutoff	1,e-003
Minimum Strain Rate Cutoff	1,e-010
Euler Domain Controls	
Domain Size Definition	Program Controlled
Display Euler Domain	Yes
Scope	All Bodies

X Scale factor	1,2
Y Scale factor	1,2
Z Scale factor	1,2
Domain Resolution Definition	Total Cells
Total Cells	2,5e+05
Lower X Face	Flow Out
Lower Y Face	Flow Out
Lower Z Face	Flow Out
Upper X Face	Flow Out
Upper Y Face	Flow Out
Upper Z Face	Flow Out
Euler Tracking	By Body
Damping Controls	
Linear Artificial Viscosity	5,e-010
Quadratic Artificial Viscosity	5,e-010
Linear Viscosity in Expansion	No
Artificial Viscosity For Shells	Yes
Hourglass Damping	AUTODYN Standard
Viscous Coefficient	0,
Static Damping	0,
Erosion Controls	
On Geometric Strain Limit	Yes
Geometric Strain Limit	1,5
On Material Failure	Yes
On Minimum Element Time Step	No
Retain Inertia of Eroded Material	Yes

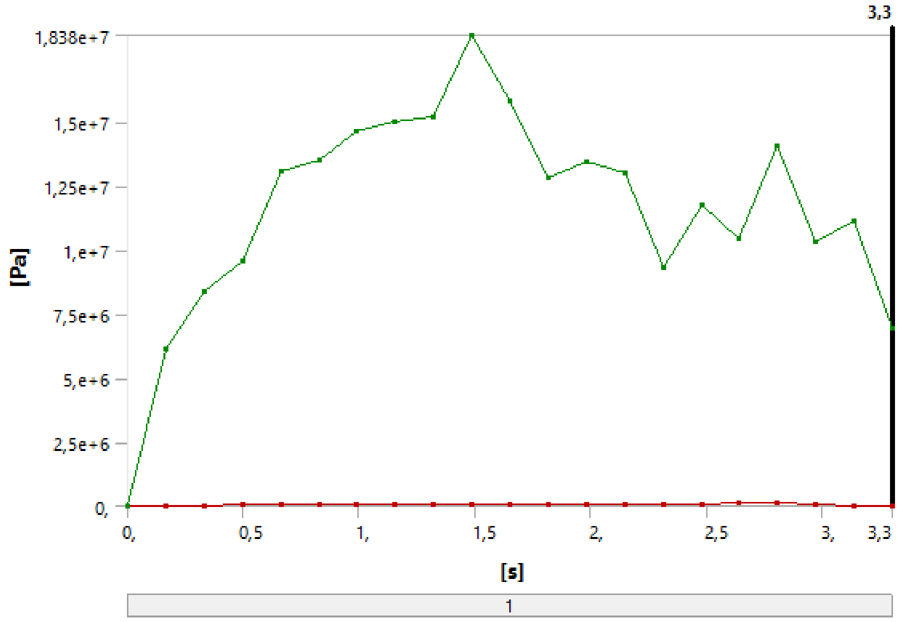
Output Controls	
Save Results on	Equally Spaced Points
Result Number Of Points	20
Save Restart Files on	Equally Spaced Points
Restart Number Of Points	5
Save Result Tracker Data on	Cycles
Tracker Cycles	1
Output Contact Forces	Off
Analysis Data Management	
Solver Files Directory	C:\Учеба кароч\Ansys\Proj_files\dp0\SYS\MECH\
Scratch Solver Files Directory	

TABLE 15
Model (A4) > Explicit Dynamics (A5) > Loads

Object Name	*Fixed Support*	*Displacement*
State	Fully Defined	
Scope		
Scoping Method	Geometry Selection	
Geometry	1 Face	1 Body
Definition		
Type	Fixed Support	Displacement
Suppressed	No	
Define By		Components
Coordinate System		Global Coordinate System
X Component		Free
Y Component		Free
Z Component		Tabular Data

Tabular Data		
Independent Variable		Time

FIGURE 1
Model (A4) > Explicit Dynamics (A5) > Displacement



Solution (A6)

TABLE 17
Model (A4) > Explicit Dynamics (A5) > Solution

Object Name	*Solution (A6)*
State	Solved
Information	
Status	Done
Post Processing	
Calculate Beam Section Results	No

TABLE 18
Model (A4) > Explicit Dynamics (A5) > Solution (A6) > Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	

Solution Output	Solver Output
Update Interval	2,5 s
Display Points	All
Display Filter During Solve	Yes

TABLE 19
Model (A4) > Explicit Dynamics (A5) > Solution (A6) > Results

Object Name	*Equivalent Stress*	*Equivalent Elastic Strain*
State	Solved	
Scope		
Scoping Method	Geometry Selection	
Geometry	All Bodies	
Definition		
Type	Equivalent (von-Mises) Stress	Equivalent Elastic Strain
By	Time	
Display Time	Last	
Calculate Time History	Yes	
Identifier		
Suppressed	No	
Integration Point Results		
Display Option	Averaged	
Average Across Bodies	No	
Results		
Minimum	0, Pa	0, m/m
Maximum	5,882e+006 Pa	0,3216 m/m
Minimum Occurs On	Solid	
Maximum Occurs On	Solid	

Minimum Value Over Time		
Minimum	0, Pa	0, m/m
Maximum	0, Pa	0, m/m
Maximum Value Over Time		
Minimum	0, Pa	0, m/m
Maximum	6,3103e+006 Pa	0,3216 m/m
Information		
Time	2,3 s	
Set	21	