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VEHICLES FOR DEEP-SEA RESEARCH

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The need for the creation of manned undersea research craft is obvious. We /283 will see what this need involves and what advantages result from the use of such craft in comparison with surface vessels.

The article lists important studies that cannot be performed by surface craft with the completeness and speed required, as follows:

(1) examination of the sea floor and water mass with the investigator's participation, to eliminate the method of multiple probing from surface craft and eliminate random results;

(2) search for sunken ships and other objects and their examination at great depths;

(3) possibility of observation at different levels with simultaneous control of instruments, which improves the quality of the research and accelerates it;

(4) collection of soil and rock samples on the sea floor can be carried out selectively, with their preliminary inspection;

(5) photography and cinematography of moving organisms, fish and sea floor will be more successful than from surface craft using submersible television and camera equipment;

(6) sonar investigations will be more complete in the study of sound channels and propagation of sound and ultrasound signals in water at different pressures, temperatures, and salinities.

It should be added that the papers of American representatives at the Tenth Pacific Scientific Congress held in 1961 indicated that the use of the bathyscaph TRIESTE, owned by the USA, produced considerable amounts of data of scientific and practical significance. Its use in undersea investigations has significant advantages over surface craft (Suzyumov, 1962).

All existing manned submarines may be divided into two types differing structurally from one another:

(a) with immersion depths from 60 to 3000 m and a displacement of 1 to 13.2 tons, for example, DENISE, ALVIN, and DEEPSTAR. They are similar to ordinary submarines in all respects, differing only in a more primitive construction, the lack of a surface motor, and in external shape and design;

(b) with immersion depths down to 11,000 m, called bathyscaphs; this type differs /2 from the first in the fact that in order to meet the strength requirements, the weight of the submarine's strength hull is so great that it cannot be compensated by its

* Numbers in the right margin indicate pagination in the original text.

buoyancy. Therefore, in order to provide for the submarine's equilibrium under water, the submarine must take on a substance lighter than water, for example, gasoline, into its outer hull. However, as it descends into great depths, the submarine loses its buoyancy because of the compression of gasoline. To maintain the buoyancy, it is necessary to have a so-called maneuverable ballast (in the form of iron pellets), which is jettisoned as required, thereby changing the weight of the submarine.

Most submarines have strength hulls of spherical shape. They are all equipped with propeller motors powered by storage batteries. Only one of them (STAR-1) uses fuel elements, operating on hydrazine and oxygen. The submerged speed of submarines ranges from 1 to 6 knots (Lisov, 1965).

The above submarines have very little autonomy, poor navigability and a short survivability in comparison with ordinary ones. However, they can perform limited tasks in calm weather when escorted by surface craft. Their raising onto surface craft in fresh weather is very difficult and involves the possibility of damage and danger to the crew. Thus, the DENISE submarine has a special carrier AMPHITRITE, and ALVIN has a catamaran-type base ship. The carrier ships are equipped with special devices for raising the submarines (Zaytsev, 1962). The submarines DOLPHIN, AUGUSTE PICCARD and ALUMINAUT, which have improved nautical qualities, are in a somewhat separate class (Lisov, 1965).

The first deep-sea submarines of the second type - bathyscaphs FNRS-3 and TRIESTE - also had poor nautical qualities; the next two, ARCHIMEDES and TRIESTE-2 - constitute a further development and have an increased underwater speed, range, and seaworthiness in comparison with the first ones (Lisov, 1965); Dionidov and Dmitriev, 1964; Piccard, 1961).

Comparison of bathyscaphs with ordinary submarines suggests some fundamental differences between them: first, bathyscaphs have negative buoyancy, which is compensated by taking on gasoline, and secondly, their descent and surfacing are carried out by changing the weight.

However, these principles were used in submarines long before the invention of bathyscaphs. Before World War II, diesel fuel was taken on into the tanks of the outer shell to compensate for the negative buoyancy due to the admission of additional ammunition aboard the submarine. In addition, the submarines were equipped with a fast immersion tank into which water was admitted to produce negative buoyancy in order to accelerate the descent. /285

Thus, there are no fundamental differences between bathyscaphs and submarines. Considering that in all war fleets, all underwater vessels, from "midgets" to vessels of several tons and up to submarine rocket carrying ones of 7000 tons, are called submarines, there is no reason to refer to underwater vehicles for scientific applications as "mesoscaphs," "bathyscaphs," or to use any other obscure and uncharacteristic names for their designation; it is best to refer to them simply as "submarines." This is the term which we will use below.

Although bathyscaphs have set world records for ocean depths, they have serious drawbacks: they have practically no autonomy. The crew can remain on board for only a few hours. Bathyscaphs are delivered to the area of submersion by a tugboat without people on board, causing conditions in which they may be lost in a storm;

(a) poor nautical qualities - a high floodability and violent motions;

(b) the use of expensive aviation gasoline as float filler constitutes a fire hazard, reduces the survivability of the vehicles, complicates the operation, and makes it more expensive;

(c) the underwater speed and maneuverability of the first bathyscaphs were very low.

Thus, submarines of both the first and second type have poor nautical qualities, may be used for performing limited tasks, and only in calm weather. They cannot be considered to be well-suited for studying ocean depths.

In discussing the question of creation of new research submarines, they should be classified, first, according to the tasks for which they are to be used, and second, according to the depth of immersion, i.e., the principal elements determining the design.

According to their depth of immersion, submarines should be divided into three types, for:

(a) small depths, down to 300-500 m, operating on the continental shelf;

(b) medium depths, down to 2000 m, for operation on the continental slope;

(c) large depths - on the ocean floor, down to 6000 m, and in ocean trenches down to 11,000 m.

The third criterion which should be used for classifying submarines is the autonomy:

(a) "autonomous" submarines have surface and underwater motors, operate independently, and reach the investigated area under their own power or towed by a surface vessel with the crew on board, and their period of autonomy is measured in days; /28

(b) submarines of "limited autonomy" have only underwater motors and are delivered to the submersion area by a surface ship; their autonomy is measured in hours;

(c) "bathyspheres," "hydrostats," and "bathystats," lowered on cables, as well as "hydrogliders" should be regarded as "nonautonomous" vehicles which, in our view, should be designated "captive and towed vehicles."

The fourth criterion in the classification of submarines is their displacement, or weight without filler: small submarines up to 30 tons, medium ones from 30 to 500 tons, and large ones, above 500 tons.

We will hereinafter consider independent submarines possessing nautical qualities that can be used most accurately and independently to solve the majority of problems involved in the study of the World Ocean. It should also be noted that submarines of limited autonomy are also necessary, although they will be used only in good weather conditions.

For a complete solution of problems involving the study of the World Ocean over its entire extent and depth, it is necessary to have several types of submarines - for small, medium and large depths.

1. Submarines For Large Depths

1. The continental shelf is most accessible to underwater studies by means of individual vehicles. Aqualungers and divers operating from surface ships can work at depths down to 40-100 m. However, the examination of considerable areas of the sea floor and the search for scientifically most interesting sections are difficult for them. Many efforts and considerable time are wasted in the lowering and raising from the depths.

For these regions, it is desirable to have small submarines with a displacement up to 1-2 tons, a limited autonomy - up to 3-4 h, and a submergence depth of 50-60 m for the work of aqualungers placed in a submersible compartment, from which they can examine areas of the sea floor for shallow water and emerge to collect samples of the soil, rocks, marine organisms, etc., and also to carry out archaeological studies. It is assumed that the submarines can be delivered to the submersion regions by a surface ship, to which they are linked by sonar equipment. A suitable /28 type of submarines in this category are those built by the Public Participation Design Office of MAI (see V. S. Makhrov's article in the present collection).

2. Small submarines with an autonomy limited to 24 h and a displacement up to 15 tons, for a submersion depth of 300 m, are delivered to the work site aboard a surface ship. Their underwater speed is 3 to 4 knots for 20 miles. For better maneuverability and in order to be able to maneuver in the depths, they should be equipped with on-board rotatable water-jet propellers located in the forebody, as in the case of the ALVIN and DEEPSTAR submarines.

3. Submarines with an average displacement of 200-300 tons, an autonomy of 5-10 days, and a submersion depth of 300-500 m. They are capable of conducting studies without an accompanying ship. The nautical qualities of these submarines will be such that they will be capable of all-weather operation, with the exception of very strong storms. They should have a surface speed of 7-8 knots with a range of 1000 miles, and a submerged speed of 3-4 knots with a submerged range of 50-80 miles at the economical speed. Submarines of this type should have exit and decompression chambers. The use of a submarine by aqualungers eliminates the time and effort required by lowering and raising. They can immediately transfer to the submarine the marine organisms and soil samples collected on the sea floor. In the submarine, the aqualungers have medical assistance available to them and if necessary, may be placed in a decompression chamber. This type of submarine may also serve as an underwater shelter when suitable modifications are made.

In addition to problems related to fishing and to marine geology, these types of submarines can perform scientific studies in most areas of oceanology. All that is necessary for this purpose is to provide them with the necessary instruments and equipment.

2. Submarines For Medium Depths

For depths of 2000 m, it is desirable to have large independent submarines with a displacement of 800-1000 tons, which can operate in regions of the continental shelf and slope, and also over the entire World Ocean within the range of their submersion depth. The main task of these submarines should be the search for new productive regions for marine industries, as well as oceanological research.

To provide for work and transit without an accompanying ship, but involving encounters with expedition surface ships to replenish the reserves, the autonomy of the submarines should be about 30 days, the navigational range, 8-10 thousand miles, and the surface speed, not less than 10-12 knots. The submerged speed may be limited to 8-9 knots with a submerged range of about 100 miles at the economical speed.

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It is possible that if heavy equipment is installed aboard the submarines, and negative buoyancy is obtained in the outer shell, a corresponding volume of filler will have to be admitted to maintain the buoyancy of the submarine under water. The filler used should be diesel fuel, not flammable gasoline.

The creation of such submarines is a more complex objective, but fully attainable by means of modern methods used in underwater shipbuilding.

If there are insufficient facilities and industrial difficulties in the creation of a completely independent submarine for 2000 m, it is necessary to construct submarines of smaller displacement (approximately 200 tons) for this depth, with correspondingly reduced speeds, operating range, and autonomy. When the studies are made in the open ocean, the submarines should operate while accompanied by a surface ship (Fig. 1).

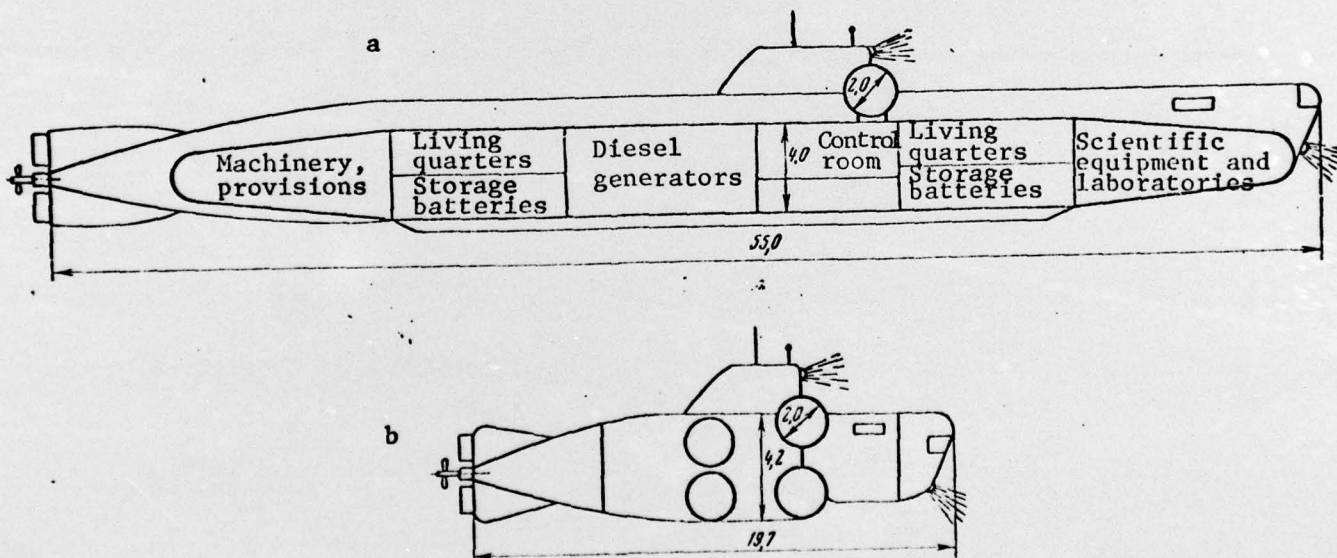


Fig. 1. Independent submarines for 2000 m.

3. Submarines For Large Depths

To study the ocean at large depths, down to 11,000 m, it is useful to have two types of independent submarines:

- (a) for regions of the ocean bed down to 6000 m (Fig. 2);
- (b) for ocean depressions down to 11,000 m (Fig. 3).

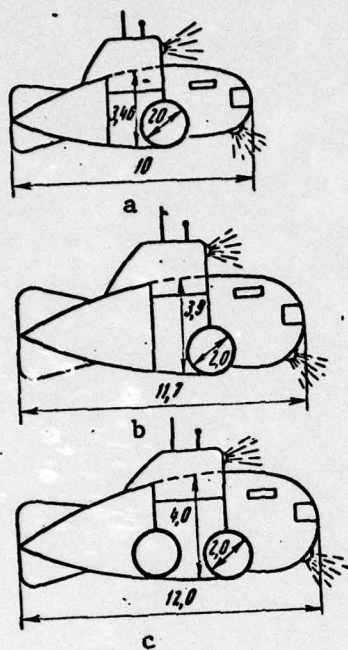


Fig. 2. Independent submarines of limited autonomy for 3000-6000 m.

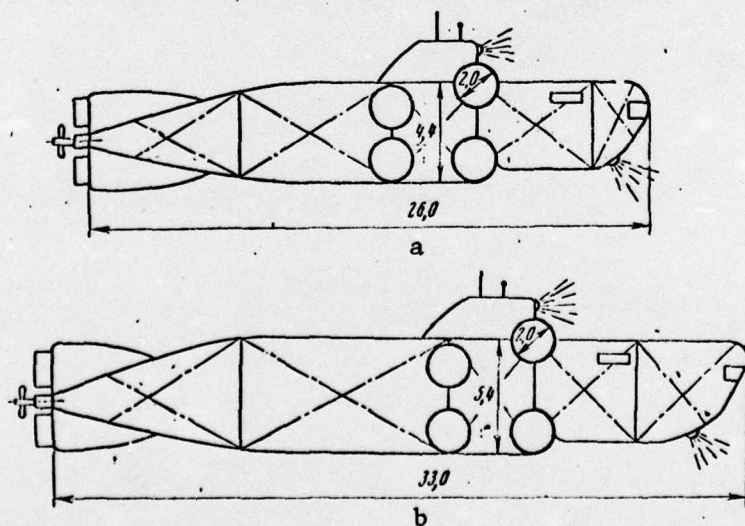


Fig. 3. Independent submarines for 6000 and 11,000 m.

The autonomy of these submarines is 10 days, operating range, 3000 miles, surface speed, 6-8 knots, and submerged speed, 3-4 knots. The displacement of such submarines will range from 250 to 700 m³, depending on the depths of submersion and the problems to be solved. In studies at greater depths, it is also desirable to have a type of small submarine of limited autonomy for the intermediate depth of 3-6 thousand m, carried on an underwater research vessel during long expeditions in the oceans. These types of submarines should be provided with two spheres with an inside diameter of 2 m: one of them made of steel, containing the crew, control equipment and scientific instruments, and the other made of glassceramic, containing the storage battery, auxiliary mechanisms, etc. Their weight without the filler should not exceed 30 tons to permit its raising from the water aboard the expedition ship. /29

A similar design should also be used for submarines of limited autonomy with a submersion depth of 11,000 m. However, these submarines will have to be towed by a surface ship to the submersion area, or special carrier ships will have to be provided for them as a result of the increase of their weight to 60-75 tons (without filler) (Fig. 4).

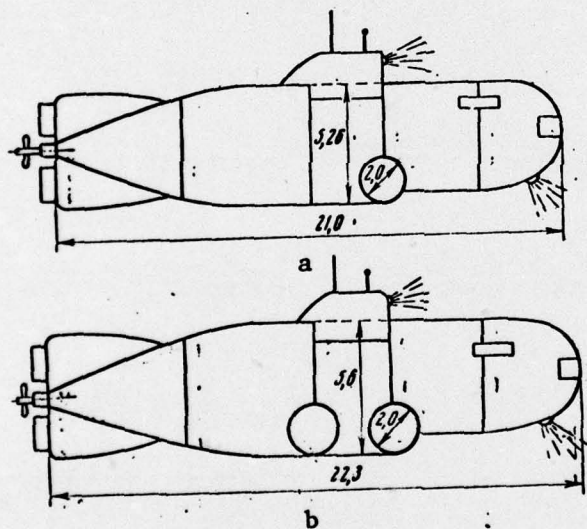


Fig. 4. Submarines of limited autonomy for 11,000 m.

The creation of all of these submarines is not obligatory, but one can select from them those types whose construction will prove desirable depending on the objectives and on the available means and industrial capabilities.

4. Proposals For the Construction of Submarines

The design should provide the above submarines with maneuverability, seaworthiness, autonomy, unsinkability, survivability and reliability, keeping in mind that they will have to navigate and operate mainly in the open ocean. Moreover, the construction of submarines and underwater vehicles should involve the use of simple, practically tested materials, machinery, and equipment, without excessively complicating the already difficult problem of their creation, or making it more expensive.

The submarines should be equipped with mass-produced motors with a high motor capacity, lead storage batteries, without energy forming and with the normal number of cycles; the filler used should be a safe product such as diesel fuel, not a flammable one like gasoline.

In designing submarines, it is necessary to see to it that they are provided with modern and advanced scientific equipment, including underwater television cameras for observation in all directions, portholes, controlled projectors, a mechanical arm for taking samples, and other devices and instruments.

To achieve a better internal layout of the machinery, equipment, and instruments, it is desirable to make the strength hull cylindrical, and if this is not possible, /292 spherical. The depth at which the use of a cylindrical hull shape becomes undesirable is determined by the thickness of its skin. The thickness of the latter should be above 15 cm, mainly for technological reasons. A significant role is also played by the diameter of the strength hull, which increases in direct proportion to the thickness of its shell. It is therefore necessary to reduce the transverse dimensions of the hull as much as possible. However, it should be considered that the minimum attainable hull diameter, whether cylindrical or spherical, should not be less than 2 m.

Strength hulls should be made of readily weldable alloy steel whose properties are fully known. The use of aluminum alloys and titanium is undesirable because of their high cost and a more complex treatment process. The promising ceramic and synthetic materials are glassceramics, fiber glass plastics, and high-strength glass. However, glassceramics thus far have had low elastic qualities, and the strength of fiber glass reinforced plastics under high variable loads decreases with time. The use of glassceramics in strength hulls can be allowed only for those hull parts in which no people are present during the submersion. Fiber glass reinforced plastics may be very profitably used in the construction of light outer hulls of submarines.

The chief reasons cited abroad and by some of our own designers in favor of the use of aluminum alloys and titanium include their low density and a strength equal to that of steel, which make it possible to obtain a small displacement without using the filler giving buoyancy to the vehicle. However, the proposed designs of submarines made of aluminum alloys and titanium have a negligible navigability and autonomy, mainly because of a small displacement, even though they are intended for navigation in the ocean.

However, in deep-sea submarines with a steel strength shell and the simultaneous admission into the outer shell of diesel fuel as the filler compensating the negative buoyancy instead of gasoline, in bathyscaphs the displacement is increased as a result of a large volume of the outer shell. The navigable qualities are thus considerably improved, making these submarines suitable for independent navigation in the ocean. Increasing the displacement cannot appreciably raise the price of a submarine, since the cost of construction of a large-volume outer shell amounts to a small fraction of the total cost. However, the expenses involved in the operation of such a submarine decrease in comparison with those involved in the operation of bathyscaphs using gasoline.

Thus, there is no point at the present time in using expensive materials for /293 the construction of strength hulls; rather, steel and limited quantities of glassceramics should be employed.

High-strength glass, whose strength is equivalent to that of high-grade steel and which is highly resistant to impact loads, could be successfully used as material for hemispheres of strength hulls: this would permit a panoramic survey of the ambient space. Unfortunately, such glass has a complex production process, and it will be difficult to obtain hull parts made of it.

A specific feature of strength hulls of vehicles consists in the fact that the thickness of their shells is substantially increased in comparison with the skin of strength hulls of ordinary submarines, reaching 15 cm or more for large depths. The formula for calculating the stresses in the skin includes the ratio of the radius of the cylinder to the thickness, and during its derivation, it is made to include the cross sectional area of the material, calculated as the product of the circumference and thickness of the skin. Calculation using this formula gives a small error that may be decreased by increasing the ratio of the radius to the thickness, and compensated by introducing a coefficient of 1.1. This error may be neglected when the ratio of the radius to the thickness is sufficiently large. In the derivation of working formulas, Shimanskiy (1948) restricted their application to "thin-walled" shells. Spherical shells with a large radius and low pressures are calculated in the same manner.

The calculated pressures for deep-sea submarines may exceed those for ordinary submarines by a factor of 10-20 or more, with a corresponding increase in skin thickness and simultaneous decrease in the ratio of the radius to the thickness, other things being equal. Therefore, the use of formulas for thin-walled shells under these conditions may result in an appreciable error. Into the formulas for the stresses in the shells of cylinders and spheres, it is more correct to introduce the area of the material as the difference between the areas calculated from the outside and inside radii, not as the product of the circumference and thickness. These will be "thick-walled" shells, in which the error in the cross sectional area of the material will be absent (Kantorovich, 1960).

For thick-walled cylindrical shells with bilateral pressure, this method of calculation was worked out by the well-known Russian scientist A. V. Gadolin. The calculations of spherical shells were performed by Z. B. Kantorovich. Thick-walled shells are not considered in structural mechanics of ordinary submarines.

The thicknesses of cylindrical shells calculated from both formulas are consistent with the pressure corresponding to depths of 2500-3000 m, and for high pressures, the skin thickness obtained from the formula for thick-walled shells will be greater than that of thin-walled shells, increasing by 10% at a depth of 6000 m. /294

The thicknesses of spherical shells determined from formulas for thick-walled and thin-walled shells for maximum stresses and depths down to 2000 m are practically the same. At a submersion depth of 6000 m, the thickness obtained from Kantorovich's formula surpasses that of the thin-walled shell by 10%, and at 11,000 m, by 22%.

Thus, the calculations of shell thickness for deep-water submarines, in contrast to ordinary ones, should be carried out by using the formulas for thick-walled shells (Kantorovich, 1960).

Using these formulas, one can obtain the stresses on the inner and outer surfaces of the shells and determine the deformations. In particular, by using them, one can readily explain the reasons for leaks of the spherical shell of the TRIESTE bathyscaph during submersion to great depths.

A second theoretical question not discussed in submarine theory is the buoyancy of the vehicles at great depths. It is well known that as it descends, a bathyscaph becomes heavier, and in order to decrease the rate of submersion, it is necessary to jettison the maneuvering ballast, and also to take on the filler into the outer hull so as to give buoyancy to the submarine.

The problem of determination of the amount of ballast and filler may be solved with the aid of Archimides' law: into the known equation of equilibrium of a body immersed in water, it is necessary to introduce the variables of specific gravity of the ambient water and filler, and weight and volume of the outer hull. A system of two equations is thus obtained - for large and for small depths; these equations are solved by successive approximations. Using them, one can calculate some the above-mentioned submarine structures, determine their displacements for different fillers - gasoline, diesel fuel and paraffin, their volumes, and the weight of the maneuvering ballast.

The calculations showed that submarines with submersion depths down to 2000 m require practically no change in buoyancy when they plunge to great depths or rise to small depths. They are no different from ordinary submarines in this regard, although in some of them it is necessary to take on a filler to compensate for negative buoyancy. However, submarines with large submersion depths must still change their buoyancy because of compression of the filler.

Changing from gasoline to diesel fuel increases the filler volume by 85%, and the submarine displacement by 65%, while the weight of the maneuvering ballast remains approximately the same in percent proportion to the displacement. If fiber glass plastic is used in outer hull designs, the displacement increase in this case will be only 40%. /29

The use of paraffin instead of gasoline increases the displacement by a factor of 2.3 and is therefore undesirable.

If gasoline were replaced by diesel fuel on the TRIESTE-II, its displacement would increase from 220 to 365 tons. Our submarine for 11,000 m with a steel outer shell and a single sphere will have a displacement of 417 tons, and with an outer shell of fiber glass plastic, 321 tons. The 52-ton discrepancy between TRIESTE-II and our submarine is explained by the fact that on the latter, the sphere has a wall thickness 3 cm greater and 5 tons heavier, and the storage battery is taken on with a higher energy.

If this is taken into consideration, the displacement figures are practically the same, so that the accuracy of the calculation may be estimated. The replacement of gasoline with diesel fuel, which is cheaper and safer, and appreciably increases the survivability of the submarines, does not entail an excessive increase in displacement, and hence, in cost.

It is desirable to have a submarine design of the following type. Independent submarines for small and medium depths should be constructed with a cylindrical strength hull. In their middle section at deck level, a strong cabin of spherical shape should be installed with portholes instead of a periscope, and the control station should be placed in it. The cabin should be connected to the strength shell by a shaft closed by a hatch. In addition, the cabin should have a hatch leading to the deck.

Small submarines of limited autonomy with a submersion depth down to 500 m should have one steel sphere as the strength hull, which should contain the control and observation stations, and the scientific equipment. A storage battery in an oil bath should be installed here in the outer hull.

On this and all other deep-sea submarines, propeller motors should also be mounted outside the strength hull. They should be preferably ac motors with a cage rotor and be powered by storage batteries through semiconductor power controlled rectifiers. Their rpm should be regulated by changing the current frequency.

Small and medium submarines of limited autonomy with submersion depths of over 2000 m and down to 11,000 m should be built with one or two spheres. In the latter case, the second stern sphere may be made of glassceramic and made to contain a storage battery and part of the auxiliary mechanisms with remote control. This sphere should not contain people during deep-sea plunges. /29

Independent submarines should have four spheres each for these depths. Two of them, located in the forebody, would be made of steel, and those in the afterbody, of glassceramic. The first two spheres should contain the observation and control stations, scientific and communication equipment, and a part of the auxiliary mechanisms. The stern spheres should contain a diesel generator with a vertical shaft, a storage battery, auxiliary mechanisms, provisions, and supplies. During long-term submersions, the submarine crew is located in the fore spheres.

To ensure better living conditions in independent submarines, in addition to small ones with a limited autonomy, it is necessary to set aside the middle ballast tank as living quarters for the crew during surface transits. This tank can be used for entry into the spheres and cylinders. It may also be made to include the volume of the cabin by making it airtight and providing it with sufficiently large portholes. This design will enable the lookouts to observe the outside situation and the behavior of the submarine during surface operation or when towed in any weather, in a location protected from blockage by waves. Particular care should be taken that the submarines have good maneuverability and maintain a steady course and depth at a speed up to 0.5 knot. This may be achieved by selecting an appropriate shape of the outer hull, for example, with flow around the buttocks in the afterpart and the installation of a developed stern assembly, and also by reducing the length-to-width ratio to 4-5 as against 8-10 for ordinary submarines.

As was indicated above, research submarines may be of the following types:

- (a) independent, with increased displacement (of hundreds of tons) and a satisfactory navigability, high speeds, adequate habitability and survivability, but a decreased maneuverability because of the comparatively high elongation of the hull. ~~These submarines can operate independently, reaching the submersion areas on their own power or by towing, arriving at the operational site as part of expeditions; and~~ WHICH
- (b) with limited autonomy, a smaller displacement (of several tons) with small elongation of the hull, good maneuverability, and a crew of 2 or 3, but with a poor habitability and decreased navigability, speeds, range, and survivability. ~~They~~ WHICH must be delivered to the submergence area aboard a surface research ship or a special carrier ship.

The construction of independent submarines of increased displacement is more expensive than that of submarines of limited autonomy and smaller displacement; /29

← Cont.
however, this is substantially offset by the fact that the surface carrier ships should be provided with equipment for servicing small submarines or be constructed along with them as their carriers.

A comprehensive study of the selection of vehicle types should be made in the future by using specialists conducting scientific marine studies in all directions, including fishing and the recovery of other products of the sea, as well as all areas of oceanology, underwater archaeology, etc.

We hope that scientists and interested organizations will take an active part in the development of this important and urgent area of national importance. A decision concerning the construction of submarines for scientific research may be expected in the near future. This makes it necessary to work out a basic line and the foundations of technical policy that should be followed in the creation of submarines to avoid dispersing the available resources.

The article is a first step in solving this question and does not claim to be exhaustive or immune to controversy in a number of the questions raised.

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