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RUS SUBMERSIBLE

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RUS SUBMERSIBLE

CONTENTS

The Rus Submersible With a Diving Depth of 6,000 Meters

927F0143A Leningrad SUDOSTROYENIYE in Russian No 7, 1991 pp 3-6

[Article by V. G. Markov, G. K. Pisarenko and Ye. M. Razumikhin]

UDC 629.127.001.2

[Text] Our country has been working to create equipment to research and assimilate the ocean for many years. Dozens of submersibles intended for operation at different depths are being used successfully by fishermen, marine geologists, and petroleum engineers, as well as by the USSR Academy of Sciences. An enormous amount of experience has already been gained in the design and operation of underwater equipment. Special materials and technologies have been developed, as have principles of safeguarding vitally important systems and devices and safeguarding the people servicing this equipment.

A rather large number of submersibles -- both habitable and uninhabitable for operation at shallow and medium depths -- exist throughout the world. Submersibles capable of diving to the limit ocean depths are another matter. They literally number in the single digits. This fact is explained by both their complexity from an engineering standpoint and the high cost of creating and operating them.

No one needs to be convinced that such submersibles are necessary. They make it possible to solve purely scientific problems and a broad range of applications problems -- from searching for sunken objects and rescuing people and expensive equipment to prospecting for useful minerals in the deepest parts of the ocean. The developed countries are sparing no resources to solve these problems. Serviceable and reliable craft capable of functioning in the deepest parts of the ocean still number in the single digits, however.

Designers from the Malakhit SPMBM [not further identified] in Leningrad have completed the design of such a submersible, and it is now being built by the shipbuilders at the LAO [not further identified]. The submersible, which has become known as the Rus, is intended to perform a set of operations in the ocean at depths up to 6,000 m. Such a diving depth will make it possible to do work in 97\% of the area of the bottom of the World Ocean.

The designers of this habitable submersible made use of the experience gained to date, and they also analyzed the level of the engineering decisions used in similar submersibles designed and constructed throughout the world in the past few years. To compare the level of the engineering decisions made, they researchers analyzed information regarding the habitable submersibles Sinkai-6500 (Japan), Nautilus (France), Alvin (United States), and Mir (Finland). The latter (two units of which exist) was designed and constructed by the Finnish firm Rauma-Repola [transliteration] for the USSR Academy of Sciences.

The virtually identical purpose and operating conditions of these submersibles have dictated their similar engineering decisions and configuration principles. All deepsea craft have pressure spheres of similar dimensions to hold their crews and their required equipment. They all also have a hard lightweight filler (syntactic foam) to ensure buoyancy, an immersible energy source (storage battery), a propeller-steering system consisting of "screw-in-nozzle"- and "screw-in-tube"-type elements, a regulating-compensating system to regulate buoyancy during the process of underwater navigation, a ballast system to position the habitable submersible when not submerged, a manipulator (mechanical arm), navigation equipment, communications equipment, sonar, various scientific-technical and special equipment, and mechanisms and systems to support the aforesaid components. All of these items are included inside an outer (nonpressure) hull the protects the equipment, gives the habitable submersible the required hydrodynamic characteristics, and determines its architecture.

These habitable submersibles are distinguished by their outward appearance and by the following elements:

-- the construction materials used in them;
-- the fundamental circuit arrangements of their systems and devices;
-- the engineering level of their electronic equipment;
-- the set of measures taken to safeguard their crew and service personnel.

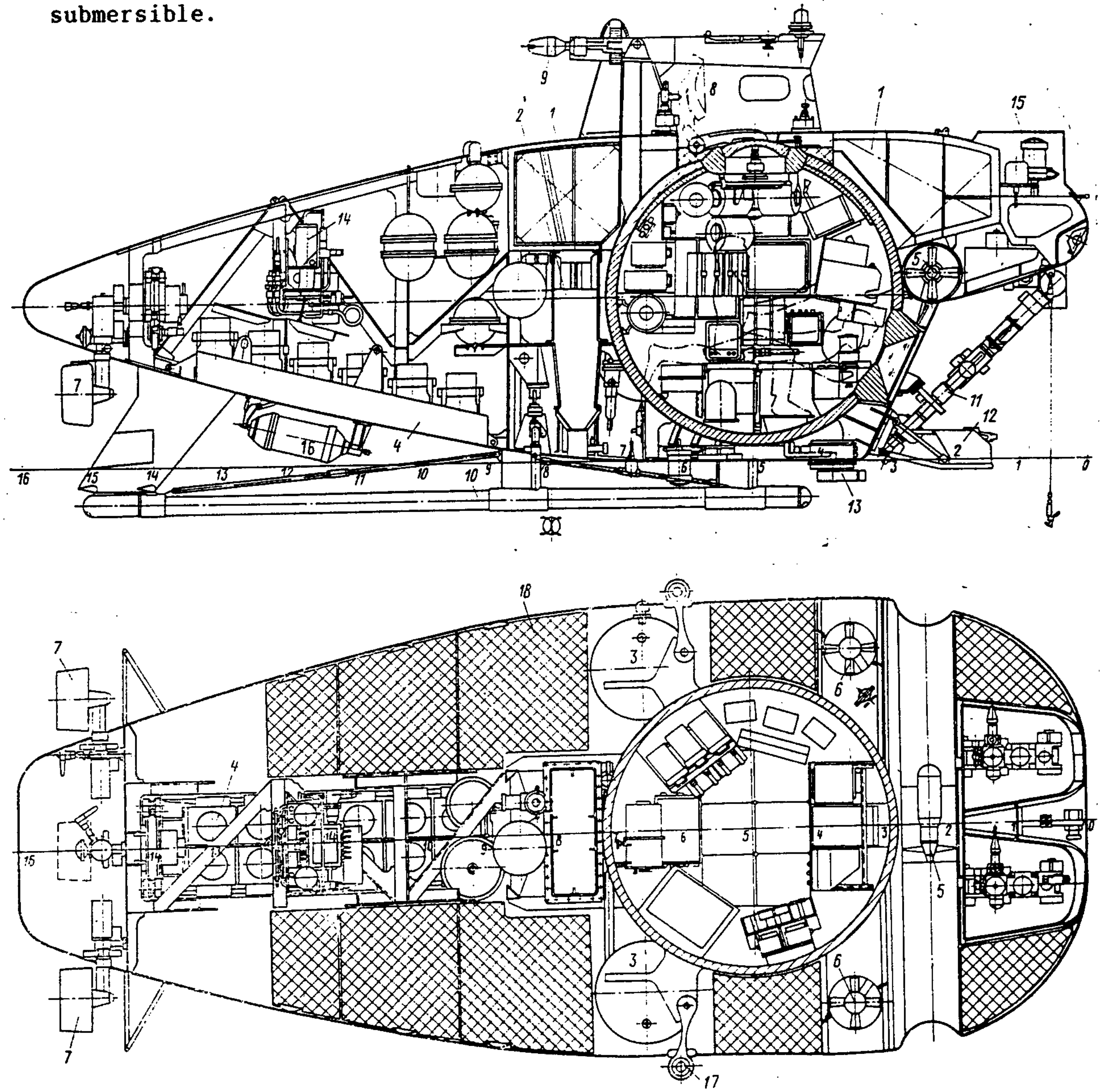
Either steel- or titanium-based alloys are generally used as the material for the pressure hull of deepsea habitable submersibles. Titanium alloys were used in the Sinkai-6500, Nautilus, and Alvin, and steel alloys were used in the Mir.

Various materials in diverse combinations are used to manufacture the outer hull. Included among them are glass-reinforced plastics, carbon-filled plastics, aluminum and titanium alloys, steel, and acrylic plastic. The methods used to secure the elements of the outer hull also differ. Welds and threaded connections are encountered, and different adhesives are used.

Different types of energy sources (both alkaline and acidic) are used. In the past few years, alkaline storage batteries (nickel-cadmium, nickel-iron) have been predominant.

The propeller-steering systems are fundamental different from one another with respect to configuration and type of energy used in the drives (electric versus hydraulic engines). The main difference between the auxiliary mechanisms used is also in the type of power required.

Figure 1. Lengthwise section (top) and plan (bottom) of the Rus habitable submersible.



1. Ballast tank
2. Bin with granular ballast (pellets)
3. Pressure (regulating) tank
4. Storage battery
5. Horizontal thruster
6. Vertical thruster
7. Vertical turning column and horizontal turning column
8. Entry hatch enclosure
9. Hoisting device
10. Supports to secure the submersible on the sea floor
11. Manipulator
12. Cargo cradle
13. Hydroacoustic station antenna
14. Hydraulic system unit
15. Antenna for underwater sonar communication
16. Bottom transponder
17. Anchor ring to secure the submersible on its carrier
18. Syntactic foam

Regardless of the design principle used, the basic power circuit of all of the submersibles under consideration are equipped with a hydraulics system that is more or less advanced. A manipulator is one user of hydraulics that all of the submersibles have in common.

The regulating-compensating systems used in habitable submersibles designed for great depths may be designed based on one of two circuits. The first is the conventional system consisting of a pressure tank designed to withstand a total sea pressure corresponding to that of the ultimate diving depth, remote control intake-discharge fittings, a high-pressure pump, and measuring and test instruments. Sea water that is taken in or discharged from the pressure tank is generally used to change the buoyancy in such systems.

The second circuit is based on a new principle. It includes a pressure tank, a remote control intake fitting, measuring and test instruments, a bin with solid granular ballast (steel or cast iron chips), and a device to meter out the granular ballast. According to this circuit, the submersible is made heavier by taking sea water into the pressure tank and is made lighter by discharging the ballast back into a special bin as before. Both schematics are combined to some degree or other in modern habitable submersibles.

A number of design measures have been taken to safeguard the crew and service personnel. These measures include the following:

-- ensuring that the habitable submersible will climb from the ocean's depths in an emergency by discharging the loads provided for such purposes;

-- ensuring that a surfaced submersible is found quickly in cases of emergency and quickly raised on board its carrier ship;

-- ensuring that crew members will be able to abandon the submersible in a special emergency device when it is on the water's surface;

-- simplifying the operation of lowering and raising the submersible from its carrier ship.

The survivability of the habitable submersible is achieved by making its main systems and devices redundant and by the presence of special emergency power sources.

A brief description of the Rus deepsea habitable submersible is now presented along with a discussion of its main differences from existing analogous submersibles.

The high level to which domestic metallurgy has brought the production of titanium alloys with specified characteristics has made it possible to use them in the structures of pressure hulls and nonpressure hulls as well as in manufacturing equipment operating in direct contact with sea water. The elimination of various materials from the structures and mechanisms of the Rus have virtually eliminated the problem of protecting the hull structures against electrochemical corrosion, which increases the submersible's overall reliability and reduces its operating costs.

Threaded connections requiring periodic inspection have been eliminated from the hull's main bearing structures. They have been replaced by welds. Glass-reinforced plastic is one of the nonmetal materials used. It forms the submersible's outer skin and is secured by a titanium fastener on the bearing frame of the nonpressure hull above the syntactic foam buoyancy blocks forming the habitable submersible's outer contour. These buoyancy blocks do not need do be replaced throughout the submersible's entire life. Access to equipment during installation and repair is gained through removable sheets located on the upper and lower parts of the outer hull along the habitable submersible's diametral plane. One distinctive difference between the Rus habitable submersible and its existing analogues is that its hull does not contain any materials facilitating the development of electrolytic corrosion.

Main Components of the Rus Deepsea Habitable Submersible

Maximum length, m	8
Maximum width, m	3.7
Maximum height, m	3.7
Hoisting mass, t	24
Diving depth, m	6,000
Sea endurance, h	
Working	12
Emergency	80
Crew, persons	2-3
Maximum velocity, knots	2.5-3.0
Energy store, kWh	50
Time required to dive/surface to/from a depth of 6,000 m, h	2.5

The crew is located inside a spherical pressure hull with an inner diameter of 2.1 m at its flat bottom sections. The design of the flat bottom sections permits the crew to assume the most convenient position (either sitting or lying) in front of the control and observation instruments depending on the task at hand. The main control elements and instruments for monitoring the status of equipment are located on a panel in the bow of the pressure hull in front of the crew. Any crew member can use the control panel from his assigned seat.

Normal operation of the habitable submersible calls for two aquanauts on board. When necessary, the crew may be increased to three persons without reoutfitting the compartment. The habitable submersible's control devices are configured so that one person handles the controls. The other crew members can attend to work left to specialists, such as geologists, ichthyologists, petroleum engineers, and fishermen. The bow section of the pressure hull contains three illuminators at an angle of 20<deg> to the horizon for visual observation of the underwater situation and to view the manipulator's live area. One illuminator is located in the diametral plane and has a diameter of 140 mm. The two side illuminators have a diameter of 90 mm. The possibility of increasing the diameters of the illuminators to 210 and 115 mm respectively is being examined.

As a power source the Rus habitable submersible uses both silver-zinc and lead-acid batteries located in the keel section of the habitable submersible in special containers filled with a dielectric fluid.

The regulating-compensating system is based on the second schematic. In other words, it has a pressure tank and bin with solid granular ballast. Besides increasing the habitable submersible's water displacement somewhat, this design decision virtually eliminates the consumption of power to dive and reduces the submersible's diving (climb) time significantly.

The ballast system, which consists of two ballast tanks and a high-pressure air system, is sufficient to keep the habitable submersible afloat with a 10\% buoyancy margin.

Electric propulsion has been used to increase the efficiency of the Rus habitable submersible's power system. Immersible 2-kW dc motors that do not require intermediate conversion of energy from the storage batteries have been used as the drive motors of the propeller-steering system and the hydraulic pumps. The habitable submersible's hydraulic system is intended primarily to support manipulator's operation, as well as for the short-term operation of individual mechanisms. The hydraulic system does not consume power in the primary mode of navigation along the ocean floor. When necessary, the system can be activated within several seconds.

Six propellers are used to move and steer the Rus habitable submersible. Three of these propellers are designed in the form of horizontal and vertical turning columns located at the stern end of the submersible. The other three are designed in accordance with the "screw-in-tube" principle. One is a horizontal turning column at the bow end, and the other two are vertical turning columns located side by side in the midsection of the hull. These propellers are used to control the ship with and without movement along all coordinate axes. The system used differs from those used in the Sinkai-6500, Mir, and Nautilus, which uses a large-diameter "screw-in-nozzle"-type propeller located at the stern end of the habitable submersible and which moves the habitable submersible in a horizontal plane at different speeds by changing its rotation frequency. In view of the fact that the main navigation mode of such devices is movement along the ocean floor at speeds up to 1 knot, such a propeller is hardly optimal from the standpoint of efficiency of the system propeller-storage battery in intermediate modes. In our case, motion at low speeds is accomplished by the simultaneous operation of one or two low-power columns operating in optimal modes. This same circuit was used in the Alvin habitable submersible after it was updated. It has also been used in a number of unmanned submersibles.

The equipment controlling all of the electric motors is located inside the habitable submersible's pressure hull. This control equipment permits smooth regulation of the motors' rotation frequency within a wide range.

A trimming device designed in the form of two loads that move inside the supports securing the submersible to the sea floor by means of a special winch and cable has been used to create static trims in the habitable submersible. The winch has a hydraulic drive. Its motion is controlled from a control panel.

The electronic equipment located on board the Rus deepsea habitable submersible performs a whole set of tasks related to navigation and special purposes. Included among the navigation equipment are a gyro course indicator, absolute and relative logs, echo sounding system, and plotting and dead reckoning systems. In addition, the habitable submersible is equipped with systems for hydroacoustic navigation based on bottom radar beacons. While in its underwater navigation mode, the Rus habitable submersible is in constant hydroacoustic contact with its support vessel. Two-way underwater sonar communication is maintained along a hydroacoustic channel. The Rus habitable submersible is equipped with a high-power hydroacoustic station that makes it possible to search for objects in circular or side scanning modes as well as to detect obstacles along a course at distances up to 750 m.

One advantage of the Rus habitable submersible that distinguishes it from its analogues is its automatic motion control system, which makes it possible to perform the most laborious searches for objects in a specified area or to reach a specified point automatically.

The manipulator makes it possible to perform a number of operations by using a special instrument located in the cargo cradle. The Rus habitable submersible may be used to help lower and raise objects weighing up to 400 kg to and from the ocean floor.

The development of a special drilling device that can be mounted in place of the manipulator is also planned. This drilling rig will make it possible to drill into the ocean floor to remove cores of all (including rocky) soil at depths up to 3 m, which will boost the habitable submersible's capabilities significantly and expand its sphere of possible users.

Extra water displacement capabilities and extra cable lines are provided so that additional equipment (televisions and scientific and special-purpose equipment) can be located on the Rus habitable submersible.

When the habitable submersible was designed, special attention was paid to the safety of its crew and service personnel. For this purpose, the habitable submersible may be raised/lowered to/from the carrier vessel without the use of auxiliary shallow-water divers or boats and floats.

Unlike the Sinkai-6500, Nautilus, and Mir habitable submersibles, the Rus habitable submersible that is now being built is equipped with an entry hatch enclosure. This enclosure worsens the habitable submersible's dynamic characteristics and increases its overall dimensions somewhat but gives it a number of advantages. The crew can, for example, open the entry hatch cover when the habitable submersible is submerged for visual observation of the surrounding conditions, for emergency ventilation of the pressure hull, or to abandon the submersible in an emergency. The height of the entry hatch enclosure ensures that it will not flood with water provided that the sea is in a state suitable for operation of the habitable submersible.

The Rus habitable submersible can make an emergency climb from the ocean's depths by dumping loads provided for such purposes. These loads are as follows: extra granular ballast (pellets), the supports to secure the submersible to the sea floor and the trimming device located in them, and the manipulator's end effectors. To prevent possible snags, the horizontal and vertical turning columns are protected by an enclosure. Equipment on the carrier vessel, as well as an ultrashortwave radio set and a flashing marker light are used to detect the surfaced habitable submersible. The Rus habitable submersible's coloration makes it highly visible on the sea surface during the daylight hours.

The Rus habitable submersible may be used along with a tethered unmanned submersible containing television and photographic equipment equipment that is capable of penetrating into narrow crevices or into the compartments of a sunken vessel for examination purposes without any risk to the habitable submersible itself. In such cases the unmanned submersible is attached to the Rus habitable submersible instead of the cargo cradle.

When the new submersible is put into operation, researchers will have a reliable modern piece of equipment that will permit them to find, study, and photograph objects located on the ocean floor. It will also permit them to conduct drilling operations, take soil samples, and raise objects to the surface.

Photo 1: A model of the Rus habitable submersible with a submersion depth of 6,000 m.

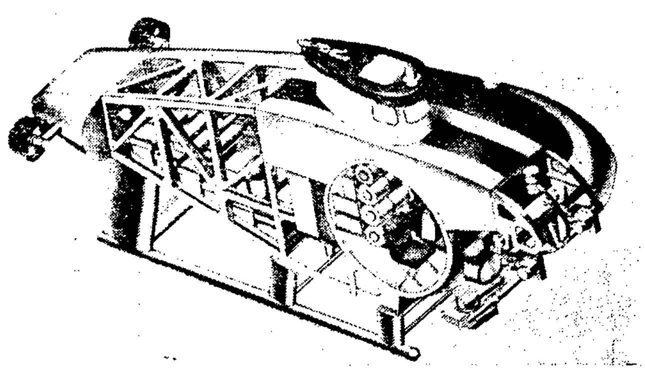


Photo 2: The Rus habitable submersible with its skin and buoyancy blocks partially removed.

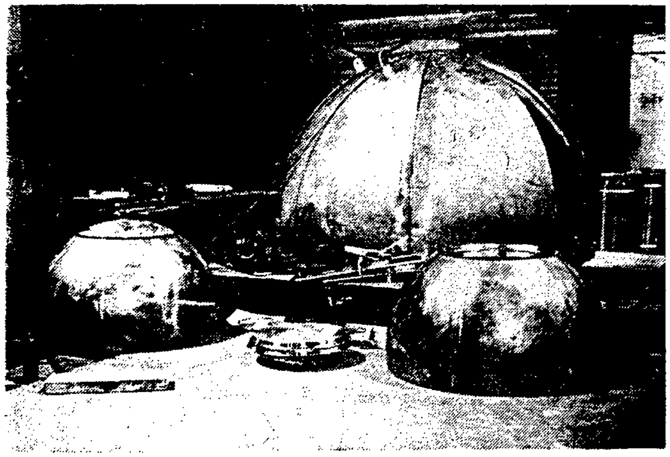


Photo 3: Assembly of the submersible's pressure hull and regulating tanks.

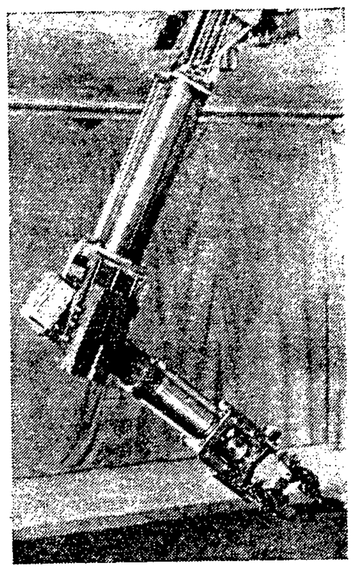


Photo 4: The end-effector of the Rus habitable submersible's manipulator.

Creating Titanium Alloy Hulls for Deepsea Submersibles Diving to Ultradeep Depths

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[V. M. Ryabov, Yu. D. Khesin, I. N. Razuvayeva, V. V. Prigoda, V. N. Kopylov, and V. S. Baldychev]

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[Text] In the past few years the highly developed countries have devoted extensive effort to finding iron-manganese concretions and other valuable hard useful minerals on the bottom of the World Ocean and preparing them for commercial recovery. The results of this work to date have demonstrated that very valuable and rich deposits are located at depths from 6,000 to 9,000 m. Habitable and unmanned deepsea submersibles have been created and used to find these deposits. From a design standpoint, these submersibles consist of spherical pressure shells made of metal or nonmetal materials and buoyancy spheres made of glass-reinforced spheroplastic (syntactic foam). The limited life of spheroplastic, its aging, and its water absorption in a comparatively small amount of operating time necessitate that currently existing deepsea submersibles be repaired periodically and that their buoyancy blocks be replaced. In addition, because these submersibles have a large number of buoyancy blocks designed for a depth of 6,000 m or more, their normal water displacement is increased significantly. This in turn increases the requirements imposed on their carrier vessels.

The objective of the work reported herein was to create a underwater unmanned submersible with a diving depth of more than 6,000 m and a relative weight that would not necessitate the use of lightweight fillers.

The research was conducted in four stages:

-- quantitative estimation of the effect that the hulls' strength and precision of manufacture have on their relative mass;

-- selection of high-strength titanium allows and development of a technology for manufacturing hemispheric stamped blanks;

-- manufacture and testing of models to assess the possibility of achieving increased strength in a titanium alloy hull for a deepsea submersible;

-- manufacture and evaluation of the reliability of deepsea submersible hulls under real conditions.

The calculations were based on computation methods and strength and stability standards adopted by the USSR Registry for steel hulls. The effect that the strength characteristics of a pressure hull's material and its deviations from correct geometric shape have on its relative mass was investigated at the same time.

Table 1 presents the calculated values of the relative mass of a titanium hull *q* (t/m^3) as a function of the material's yield strength and the submersion depth. These values were obtained by proceeding from the condition that the hull is a closed spherical shell made of titanium alloys with a density of about 4.5 t/m^3 with a permissible deviation from correct form *f* equal to 0.02 of the shell's thickness.

In order for a hull to be suitable for use in a deepsea submersible at the depths under consideration without the use of a lightweight filler, it must have a relative mass *q* within the range from 0.6 to 0.7. As is evident from Table 1, for a depth of 6,000 m this requirement may be met by using titanium alloys with a yield strength of 900 MPa. For depths of 8,000 m this requirement can only be satisfied by using alloys with a yield strength of 1,200 MPa.

Table 1. Relative Mass (*q*) of a Spherical Titanium Hull as a Function of the Material's Yield Strength and Submersion Depth

Immersion Depth, m	Yield Strength, MPa			
	900	1,000	1,100	1,200
6,000	0.674	0.621	0.580	0.547
8,000	0.863	0.793	0.736	0.690
9,000	0.955	0.876	0.812	0.760
10,000	1.045	0.958	0.888	0.830
11,000	1.132	1.038	0.962	0.900

Greater depths require a revision of the accepted values of *q* even in the case where a titanium alloy with a yield strength of 1,200 MPa is used. It is necessary to give consideration to the fact that a deviation of the hull's shape from the ideal will increase *q* somewhat (Table 2). It is thus possible to significantly reduce a hull's relative mass by doing two things simultaneously, specifically, by increasing the strength of the hull material and by manufacturing the hull with a high degree of precision.

Table 2. Relative Hull Mass as a Function of Deviation From Correct Form (*f*) and Yield Strength of Hull Material for 9,000-m Submersion

Yield Strength, MPa	Value of *f*		
	0	0.02	0.05
900	0.934	0.955	0.982
1,000	0.856	0.876	0.903
1,100	0.791	0.812	0.838
1,200	0.738	0.760	0.786

-- manufacture and evaluation of the reliability of deepsea submersible hulls under real conditions.

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Achieving the required strength level ($\sigma_{0.2}$ = 900 to 1,200 MPa) in titanium alloys while maintaining sufficiently high serviceability is a very complex task. The presence in a hull of stress concentrators in the region of the coamings of the illuminator hatches and different types of stiffeners result in the appearance of flexural stresses that affect resistance to the development of cracks in the metal. As is well known, increasing strength is inevitably linked with reducing the critical value of stress intensity. In turn, both the level of the strength values and resistance to crack propagation (particularly in a corrosive medium) are determined not only by the degree to which the alloy has been doped but also by its structural and textural state. In titanium alloys with a sharp prismatic texture, the difference in yield strength as a function of direction in which the specimen has been cut out may amount to as much as 200 MPa, and the value K_{ISCC} may differ by a factor of 2.

In view of this fact, the selection of the titanium alloy must be simultaneous with the development of the hot plastic deformation modes used to obtain the most favorable structural and textural state.

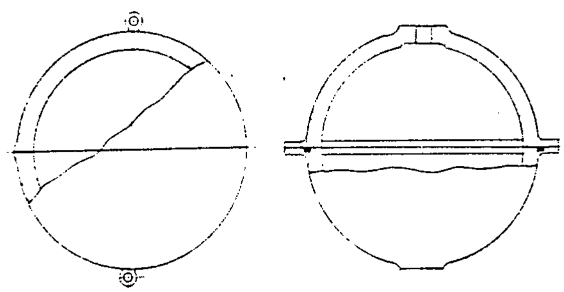

Figure 1. The spherical pressure hull in its welded (a) and threaded (b) versions.

It is known that pseudo-α-alloys represent the optimal version of a material for hull structures from the standpoint of combining basic characteristics and and above all weldability. The drawbacks of this type of alloy include the impossibility of significantly increasing their strength by heat treatment. The yield strength of the strongest alloys of this type is between 800 and 850 MPa.

The highest strength characteristic values are achieved in two-phase (α+β)-alloys. Alloys of this class are weldable within limits. In other words, they require special measures to ensure satisfactory plasticity in the heat-affected zone. In addition, they are significantly more sensitive to the type of structure than are α-alloys. Consequently, it is necessary to create an extremely homogeneous and fine-grained structure so as to avoid a sharp drop in plastic properties upon subsequent hardening heat treatment.

In view of what has been stated, a series of research studies was performed. Two materials were selected on the basis of the said studies: a pseudo-α-alloy and an (α+β)-alloy. A hot plastic deformation regimen was then developed that ensured a controlled structure and texture in spherical stampings with a diameter of 500 mm and a wall thickness of 30 mm.

The mechanical properties of stamped blanks determined on specimens cut out in the vertical and chord directions are presented in Table 3. As follows from the table, the values of the strength properties are virtually identical in both directions and confirm the possibility of achieving a value of $\sigma_{0.2} \geq 900$

MPa in a pseudo-α-alloy and $\sigma_{0.2}$ ≥ 1,000 MPa in an (α+β)-alloy. In addition to having the specified strength property values, the structural state described above provides extremely high plastic characteristics.

Table 3. Mechanical Properties of Hemispheric Stampings Made of Different High-Strength Titanium Alloys (C = chord; V = vertical)

Alloy Type	Lot No.	Direction of Specimen	Mechanical Properties				
			σ, MPa	$\sigma_{0.2}$, Mpa	δ, %	ψ, %	KCU, kJ/m^2
Pseudo-α-alloy	I	C	988—1002 / 994	924—956 / 939	15.2—17,6 / 16,3	45,2—46,3 / 45,7	560—660 / 620
		V	976—997 / 989	920—936 / 927	16,4—18,4 / 17,5	44,8—48,6 / 45,9	560—660 / 620
	II	C	1051—1081 / 1062	989—1002 / 995	14,0—16,0 / 14,9	40,4—48,4 / 43,8	400—410 / 400
		V	1035—1063 / 1058	964—1001 / 978	12,0—18,0 / 15,0	42,5—53,4 / 46,7	510—536 / 520
(α + β)-alloy	I	C	1062—1100 / 1080	1017—1055 / 1036	11.2—15,0 / 16,0	49,0—62,5 / 54,5	499—566 / 541
		V	1062—1100 / 1080	1017—1055 / 1036	11,2—15,0 / 12,7	34,0—46,5 / 39,4	531—603 / 562
	II	C	—	—	—	—	—
		V	1225—1229 / 1127	1081—1092 / 1088	16,0—18,0 / 16,7	44,1—53,3 / 48,3	563—581 / 570

To further increase the strength of a two-phase alloy, a set of research studies was conducted to select hardening heat treatment regimens. On the basis of these studies two regimens were recommended for commercial testing.

As follows from Table 4, heat-treating stamped blanks in accordance with the specified regimens makes it possible to achieve a value of $\sigma_{0.2}$ ≥ 1,200 MPa with sufficiently high plastic characteristic values.

Table 4. The Effect of Hardening Heat Treatment on the Mechanical Properties of Hemispheric Stamped Blanks Made of a Two-Phase Alloy (Vertical Specimens)

Heat Treatment Regimen	Mechanical Properties				
	σ, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %	KCU, kJ/m^2
Initial State	1225—1129 / 1227	1081—1092 / 1088	16,0—18,0 / 16,7	44,1—53,3 / 48,3	563—581 / 570
Regimen 1	1286—1316 / 1306	1206—1261 / 1226	10,0—12,0 / 10,6	30,6—37,1 / 33,7	314—390 / 354
Regimen 2	1306—1322 / 1313	1216—1261 / 1238	10,8—13,2 / 12,1	38,6—41,7 / 40,1	311—427 / 361

NOTE: Regimen 1 = 820° for 2 hours in water followed by 520° for 10 hours in air; regimen 2 = 850° for 2 hours in water followed by 550° for 10 hours in air.

To verify the effectiveness of the research studies conducted, the test alloys were used to manufacture a model with a diameter of 500 mm for operation at a depth of 6,000 to 6,500 m with the strength margin accepted for unmanned deepsea submersibles. The relative mass of the hull as a function of the submersible's design was varied from 0.52 to 0.57.

To be able to compare the results of tests on hulls made of the said alloys with different strength levels, the theoretical breaking pressure at $\sigma_{0.2}$ = 1,000 MPa was assumed to equal 1. Both detachable instrument casings with a groove for sealing with a rubber and welded casings were subjected to tests.

As is evident from Table 5, the increase in yield strength from 900 to 1,000 MPa (i.e., by 11%) results in an increase in the sphere's load-bearing capacity of 25 to 32%. A further increase in yield strength to 1,200 MPa (a 20% increase) results in only a 15% increase. The failure mechanism changes as well: Instead of a loss in stability there is breaking from a shear associated with the sharp increase in sensitivity to stress concentrators.

Table 5. Results of Tests of Models With One and the Same Shape by Loading With Hydrostatic Pressure Until Failure

Material of Model	Metal's Yield Strength, MPa	Casing Thickness, mm	Relative Breaking Pressure	Type of Failure
Pseudo-α-alloy	900	10	0.8	Loss of stability at pole
(α + β)-alloy	1,000	10.2	1.05	Loss of stability at contour
(α + β)-alloy	1,000	10.0	1.06	Same
(α + β)-alloy	1,000	9.5	1.00	Loss of stability at pole
(α + β)-alloy after heat treatment	1,200	9.8	1.15	Shear along contour around groove under seal

In view of this fact it became necessary to make an additional assessment of the reliability and serviceability of structures made of an (α+β)-alloy with a yield strength of 1,000 MPa. For this purpose, models were subjected to cyclic tests and to tests under protracted static loads of external hydrostatic pressure. The test results demonstrated that the reliability of structures during the process of their operation depends significantly on the magnitude of the stress concentration and the site of its location.

Increasing the width of the sealing groove from 3.5 to 7 mm while keeping the remaining geometric parameters unchanged caused the model to experience a shear fracture along the contour at pressures significantly below the theoretical pressures. The same model, when tested under cyclic loads, demonstrated that the formation and slow development of cracks of the nature of shear cracks is possible at pressures corresponding to the threshold operating loads. The development of such cracks increased as the number of loading cycles increased. In the final analysis, this results in a shear fracture at the groove after 7,500 cycles.

Analogous results were obtained on a model with a groove width of 3.5 mm that had two notches about 3 mm deep on its surface. After 250 cycles under cyclic loading at the threshold operating load, cracks began to develop slowly on the bottom of the notches.

The tests conducted thus demonstrated that when high-strength materials with $\sigma_{0.2} \geq 1,000$ MPa are used, the reliability of the hull structure can only be ensured by eliminating all possible stress concentrators or by shifting them to the zone of lesser stresses. Very similar results were obtained in welded models made by using argon arc welding. At loads equal to the maximum permissible loads, the models were held for 3,000 cycles without damage. The results obtained made it possible to develop a structure for the pressure hull of a deepsea submersible and a technology to manufacture the said hull.

The studies conducted were used in manufacturing unmanned deepsea submersibles with spherical hulls from an (α+β) alloy with a yield strength of 1,000 MPa. The results of tests conducted in the Pacific Ocean at a depth of more than 6,000 m demonstrated their high reliability and serviceability.

Conclusion

The following were among the accomplishments of the work conducted:

-- a quantitative estimate of the effect that the hull's strength and the precision of its manufacture have on its relative mass;

-- selection of the composition of high-strength titanium alloys and development of processes to use them to manufacture hemispheric stamped blanks with a controlled structure and texture that are regulated during the manufacturing process;

-- bench tests of full-scale models of hulls in their welded and threaded version under static and cyclic loading. These tests made it possible (for the first time in world practice) to create a series of unmanned deepsea submersibles with a small water displacement and with a pressure hull with a relative weight of at least 0.6 t/m^3 for depths of more than 6,000 m with no need for expensive and scarce lightweight fillers.

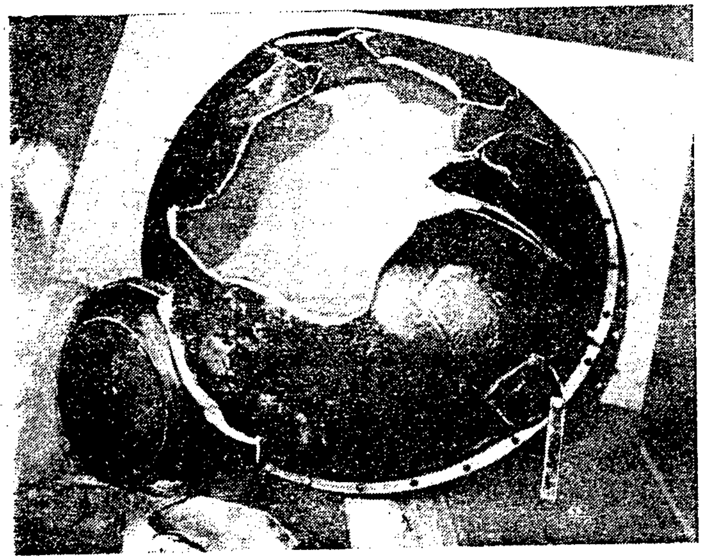

Photo 1: View of a model of the pressure vessel after hydrostatic breaking tests

The Motion and Hardware Control System of the Rus Submersible

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[Article by A. N. Babayev, A. E. Byunau, Yu. B. Yudin, and K. A. Yakobson]

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[Text] The Flyuorit-810 motion and hardware control system for the Rus submersible is intended for use in controlling the submersible's motion in remote control and automatic navigation modes. It is also intended for use in setting up remote control of the submersible's hardware components. The Flyuorit-810 system is the first domestic submersible motion control system developed by using digital computer technology. The use of digital computer technology in the motion control system made it possible to significantly increase the efficiency of both the system's operators and the submersible itself during exploratory and research work.

The experience that has been gained in operating the first and subsequent submersibles has demonstrated that the automata conventionally included in a submersible's motion control system to control its course, trim, and diving depth do not provide the desired effect when operated in a submersible. Submersibles are used primarily to study specified sections of the ocean floor and/or objects located on it. During the process of their operation, submersibles must remain suspended in some specified point in space, land on underwater objects, move close to the ocean floor along a specified trajectory, etc. Such modes of operation require coordinated control of the submersible's actuators by using conventional automata with respect to the individual coordinates of the motion. This is a new and rather complex task. Until recently such modes were executed by an operator by remote control of the submersible's actuators. Individual coordinates of a motion could be maintained at the required level automatically. Simultaneous control of several coordinates and consequently several actuators under conditions of rigid time and maneuvering precision indicators requires a high degree of professionalism on the part of operators or a high degree of automation of motion control.

Total automation of three-dimensional motions within the framework of conventional analog motion control systems is virtually impossible because the equipment used to achieve this automation cannot always be configured in the space of a submersible's pressure hull that has been allocated for the motion control system. Furthermore, a number of tasks are virtually impossible to perform by means of analog technology. Examples of such tasks include tasks related to processing the information arriving from hydroacoustic transponders or television cameras. Since the appearance of digital computers small enough to be located on board a submersible that have the technical capabilities (speed, amount of memory, etc.) required to perform the set of tasks entailed in motion control and to operate under marine conditions in accordance with the requirements stipulated by the USSR Registry, the integrated automated control of a submersible's motion has become a reality. It should be noted that in addition to performing the tasks entailed in motion control, the digital computer included in the submersible's motion control system also performs the following no less important functions:

-- organize a summary display of the submersible's motion parameters on a television display screen as the submersible executes a three-dimensional maneuver (remote control is possible in such cases);

-- operate in an "adviser" mode (the operator does the actual controlling, but the digital computer issues recommendations regarding using the actuators).

Setting Up Automatic Three-Dimensional Maneuvering of the Rus Submersible

The Flyuorit-810 system executes the following maneuvering modes when controlling the motion of the Rus submersible:

-- remote control of the forces and moments created by the submersible's actuators (the submersible's motions are controlled by an operator);

-- automatic movement to a specified depth followed by stabilization of the submersible at that depth;

-- movement to a specified trim and subsequent stabilization at that trim;

-- movement to any specified course and subsequent stabilization relative to it;

-- stabilization of running speed relative to the specified value;

-- stabilization of distance from the ocean bottom, including equidistant motion along the surface of the ocean floor;

-- motion along a trajectory specified in a horizontal plane by parallel sounding lines or an Archimedian spiral in a coordinate system formed by hydroacoustic transponders;

-- off-line control based on the five degrees of the submersible's freedom (course, trim, distance from the bottom, running speed, and speed of sideward movement).

In addition to the aforementioned modes, docking with an underwater object and landing either on the said object or on the ocean floor is also possible.

The maneuvering of the Rus submersible is controlled by using the following actuators:

1) a horizontal turning column located at the stern end of the submersible and consisting of a fixed-pitch screw located in a turning nozzle (the nozzle and screw turn as a single unit);

2) two vertical turning columns consisting of the same elements used in the horizontal turning column and located at the stern end in the port and starboard;

3) a horizontal thruster in the forma of a fixed-pitch screw located in a tube (the horizontal thruster is located in the submersible's bow);

4) two vertical thrusters analogous to the horizontal thruster but located close to the submersible's pressure center (they are henceforth considered as a single actuator);

5) a regulating-compensating system;

6) a bin of pellets and a device to meter their discharge;

7) a trimming device in the form of a weight that moves along the submersible's lengthwise axis.

The submersible is balanced from a buoyancy standpoint in a remote control mode by taking water into the regulating tank or else by discharging the pellets from the bin. The submersible is balanced from a trim standpoint in a remote control mode as well, but by moving the load of the trimming device. The remote control mode has been used because of the constraints regarding the number of activations of the hydraulic system's slide valves that control water intake into the regulating tank and movement of the trimming device's load as well as because of constraints regarding the reserve of pellets in the bin and size constraints imposed regarding the volume of the regulating tank.

The structure of the Flyuorit-810 system that executes the three-dimensional maneuvering modes may be represented in terms of a sequence of hierarchical levels. Automata providing selected forces and moments are located at the bottom level, local automata controlling the individual coordinates of the submersible's motion (course, depth, distance from the bottom, trim, and running speed) are at the middle level, and three-dimensional maneuvering automata (effecting motion along a specified trajectory, motion along the ocean's bottom, and off-line control) are at the top level. The automata at all these levels are implemented in the on-board digital computer.

The bottom-level automata compute the specified rotation frequency of the propeller screws and the required turn angle of the submersible's actuators as a function of the forces and moments specified either by an operator or by the mid-level automata. The local automata at the middle level control the individual coordinates of the submersible's motion in accordance with the values of these coordinates as specified by an operator or by the top-level automata. The output values of these automata are specified values of the forces and moments. The top-level automata issue specified motion coordinate values for the local automata at the middle level.

Table 1 presents those actuators that are used in the various maneuvering modes.

Table 1. Use of the Submersible's Actuators in Maneuvering Modes

Maneuvering Modes	Actuators						Notes*
	A	B	C	D	E	F	
Control of yaw moment	-	+	+	-	-	+	1, 2, 3
Control of trim moment	-	-	+	-	+	-	1, 4
Control of lengthwise force	+	-	+	-	-	-	1, 2, 5
Control of vertical force	-	-	+	-	+	-	1, 4
Automatic course control	-	+	+	-	-	+	1, 2, 3
Automatic trim control	-	-	+	-	+	-	1, 4
Automatic control of depth or distance from bottom	-	-	+	-	+	-	1, 4
Automatic velocity control	+	-	+	-	-	-	1, 2, 5
Automatic trajectory control	+	-	-	-	-	+	6
Automatic control of motion along bottom	+	-	+	-	+	-	4, 6
Off-line control	+	+	+	+	+	+	6

Key: A = horizontal turning column screw; B = vertical turning column nozzle; C = vertical turning column screws; D = vertical turning column nozzles; E = vertical thruster; F = horizontal thruster.

Notes: 1 = actuator is selected by the operator; 2 = vertical turning column nozzles should be turned at an angle of $0 \leq \delta_{vert.turn.col.} < 90^\circ$; 3 = the rotation frequency of the horizontal turning column screw when a horizontal turning column screw is used should be >2 rotations/s; 4 = the vertical turning column nozzles should be turned at an angle of $0 < \delta_{vert.turn.col} \leq 90^\circ$; 5 = the turning angle of the horizontal turning column nozzle when a horizontal turning column screw is used should be <90°; 6 = actuator is selected automatically.

The function of the bottom-level automata is to solve a system of linear algebraic equations. The results of these equations are the values of the required screw rotation frequency and specified turning angle of the turning column nozzles. The solution is corrected automatically if the frequency and turning angle values obtained are in excess of the maximum permissible values.

The local automata at the middle level consist of the following program units:

-- filtration and/or restoration of the controlled coordinates;
-- computation of the specified value of the forces and moments.

Filtration and/or restoration of the controlled coordinates is accomplished by using status observers. In the algorithm for computing the specified forces and moments a distinction is drawn between "major" control (i.e., control of a transition) and "minor" control (i.e., stabilization of a controlled coordinate relative to a specified value). In the first case, the control algorithm is based on the theory of control that is optimal from a speed standpoint. In the second case it is based on control that is optimal from the standpoint of the linear square quality criterion. This approach to constructing the algorithm made it possible to provide the required submersible maneuverability and to hold it at a specified point reliably.

The algorithms for the functioning of the top-level automata are dictated by the specific type of mode (motion along a specified trajectory, motion along the bottom, etc.). An automaton to control a submersible's motion along the bottom of the ocean may be cited as one example of this type of automaton. The automaton operates on the basis of information received from an echo sounding system, log, and trim indicator and issues settings for the local automata controlling the moving speed, trim, and distance from the bottom.

Another example of a top-level automaton is an automaton controlling motion along a specified trajectory. Information about the submersible's position arrives from hydroacoustic transponders and is processed in the navigation system. The automaton issues settings for the local course and moving speed automata.

The automaton responsible for the mode of off-line control of the submersible's motion with respect to its five degrees of freedom is especially important. In this mode, the operator can implement manual control of any one selected coordinate while the remaining coordinates are stabilized automatically. A particular case of this type of control occurs when the submersible is suspended at a point under conditions where disturbances (a current, the operation of a manipulator, etc.) are acting upon the submersible. The need for such a mode is dictated by the presence of intersecting links in the submersible's dynamics equations and the configuration of the submersible's actuators. For these reasons, manual control of some individual actuator results in forces and moments that in turn change not only the necessary coordinate but several other coordinates as well. In a number of cases, these changes may be significant. "Fine" maneuvers such as landing, tracking underwater objects, etc., in a purely manual control mode are highly labor-intensive from the standpoints of the energy and time required to execute the maneuver and require a highly qualified operator. The system's automatic control mode makes the operator's work much easier when work is being performed close to the bottom of the ocean or when the submersible is landing either on the ocean floor or on some object.

System Hardware

The system's hardware is based on a centralized single-processor structure. The following are included in the system:

-- a Lada-7 digital computer;
-- an I/O device;
-- interfaces with the single-channel system and hardware;
-- a control panel with a television data display screen.

The Lada-7 digital computer was developed especially for use on the Rus submersible and has the following basic characteristics:

Instruction system	Elektronika-60 type
Speed of register-register-type operations, millions/s	1
RAM, kbyte	32
User ROM, kbyte	32
External interface	MPI
Power requirement, W	60

The digital computer inputs information about the submersible's status along with hardware from the respective input devices. This information is then converted, the actuator control actions are computed in accordance with the control algorithms, the control actions are issued to the actuators by the respective output devices, and a video frame is formulated for output to a television display screen.

The information I/O device includes the following:

-- an analog-to-digital converter designed to receive 32 analog signals with a voltage up to ±10 V;

-- two digital-to-analog converters with four analog outputs each and with an output voltage up to ±10 V;

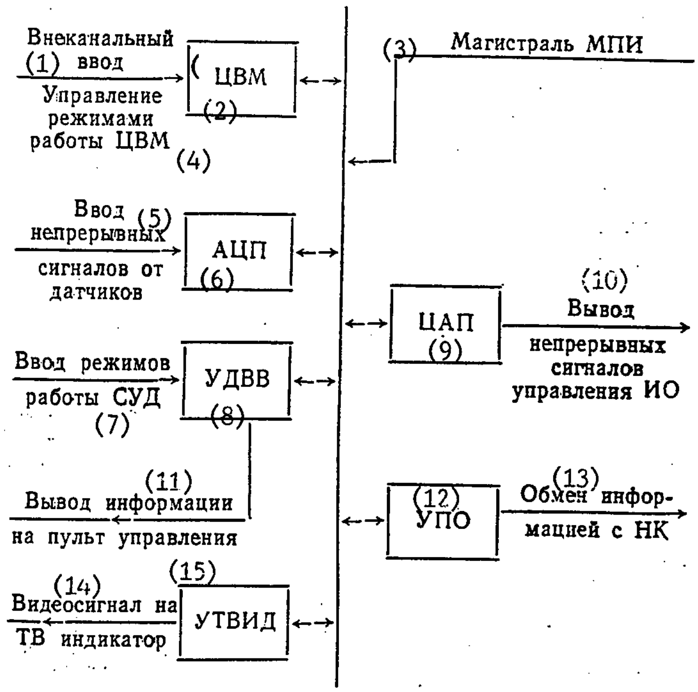
-- four digital I/O devices designed to receive 16 digital signals of the "dry contact" type and to output 10 digital signals each;

-- a television display screen controller;

-- a sequential exchange device to communicate with the navigation system.

The digital computer and I/O devices form the computer nucleus of the system (circuit). The interface with the single-channel system and hardware form the analog part of the system. They include the following: photosensitive rectifiers that serve to convert the ac signals arriving from the type VT sensors, scaling operational amplifiers, relay and linear power amplifiers, relay-type switching elements, tumblers switches, and other switches.

Figure 1. Flowchart of the computer nucleus of the Flyuorit-810 system.



1. Extrachannel input
2. Digital computer
3. MPI (microprocessor interface) bus
4. Control of the digital computer's operating modes
5. Input of analog signals from sensors
6. Analog-to-digital converter
7. Input of the motion control system's operating modes
8. Digital I/O device
9. Digital-to-analog computer
10. Output of analog actuator control signals
11. Output of information to the control panel
12. Sequential exchange device
13. Exchange of information from the navigation system
14. Video signal to a television display screen
15. Television display screen controller

The devices of the interface with the single-channel system and hardware perform the primary conversion of signals from the sensors and the signaling devices, amplify the power of the control signals, and (when necessary) provide galvanic separation of the system's input and output circuits.

The control panel serves to specify the operating modes of the digital computer and motion and hardware control system and input specified control parameter values. Information about the parameters of the submersible's motion and the status of its hardware, the required parameter values, and the results of a test check to determine whether the system's hardware is in correct working order are output to a television display screen mounted on the panel.

From a design standpoint, the system's panel has been fashioned in the form of two instruments whose shapes conform to the dimensions of the submersible's pressure hull at the place where they are configured. The computer nucleus of the system is a Lada-7 digital computer in the form of a separate device and I/O devices located in a single-level instrument bay 500 mm wide. The I/O devices themselves have been designed in the form of models of the PROSEM [not further identified] design. The interfaces with the single-channel system and hardware are also designed in the form of modules and are located in a similar single-level instrument bay.

In addition to the aforesaid instruments, the Flyuorit-810 system also includes a pendulum-type trim angle-data transmitter. The system's instruments do not occupy more than 230 m^3 of space and weigh 140 kg. The system is powered from an ac current of 27 V. The maximum power requirement does not exceed 300 W.

If the submersible's actuators have a hydraulic drive instead of an electric drive, the system may also contain additional electrohydroaulic instruments for bang-bang or proportional control. These devices have both outboard and in-hull designs.

When necessary, the system may also execute the following:

-- test checks and diagnosis of the submersible's actuating mechanisms and systems based on specified algorithms;

-- a simulated system operating mode to train operators.

These operating modes are possible while the submersible is on its carrier provided that an additional PC-type machine (for example, an Elektronika-85) is also provided.

Conclusion

Adding a digital computer to the motion and hardware control system has made it possible to produce the first domestic system for automatic three-dimensional maneuvering of submersibles, to improve the services provided to submersible operators significantly, and to increase the degree of standardization of the engineering decisions used when developing systems intended for analogous purposes. Suffice it to say that based on the decisions made when the Flyuorit-810 system was designed, the time required to design and deliver the Naudi motion and hardware control system for the Ikhtiandr submersible was greatly reduced.

Using a digital computer made it possible to reduce the mass and space occupied by the motion and hardware control system. When compared with previous submersible control systems, the new system weighs only half as much, and the amount of space it occupies has been reduced by a factor of 1.5.

The system's computer nucleus may be used as a peripheral computer in large control systems with a distributed structure inasmuch as the computing power of the Lada-7 digital computer is inadequate for it to serve as the central nucleus of such a structure. In addition, it may be used as a basis for configuring control systems to control not just the motion but also any other parameters that lend themselves to the information representation via an interface that may be connected to the Flyuorit-810 system.

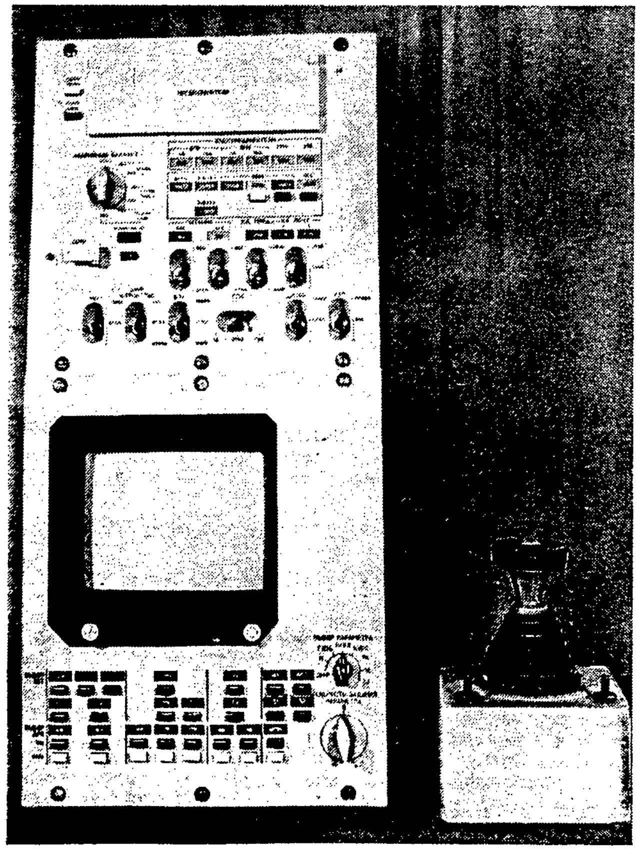


Photo 1: Panel and single handle of the Flyuorit-810 control system.

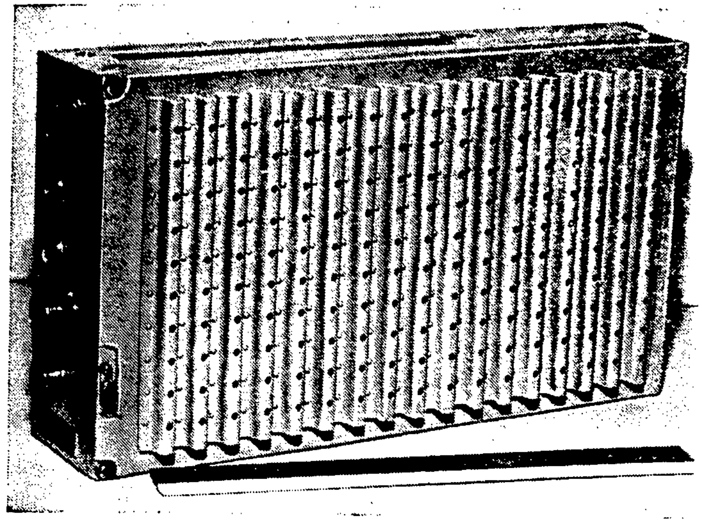


Photo 2: Lada-7 on-board digital computer

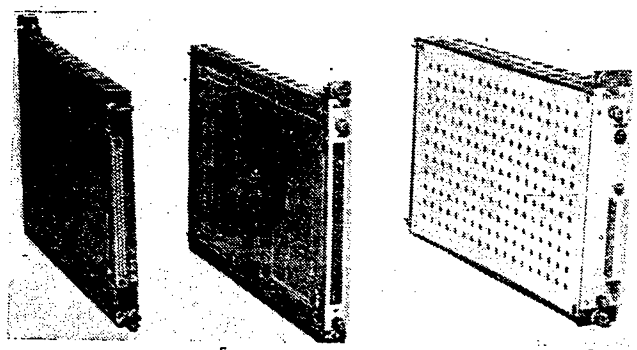


Photo 3: UDC [not further identified] modules of the Flyuorit-810 system.

- END -