This book has been written based on the textbook "Submarine Design", which has been recommended by the Ministry of Education of the Russian Federation for students of institutions of higher education, specialising in "Shipbuilding". It is published in the year of a centenary anniversary of submarine professional design in Russia.

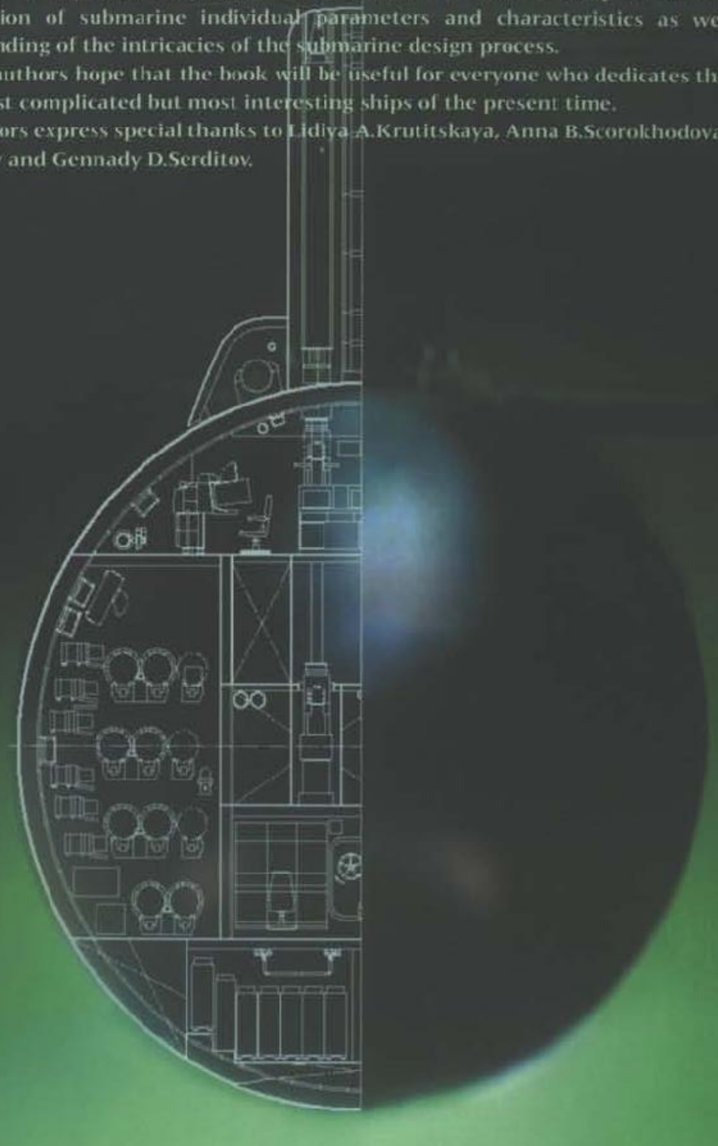
The book is published with the permission of the authors and the consent of the St.Petersburg State Maritime Technical University.

The book explores methodological issues, theory of submarine design, general methods of submarine displacement and its trimming determination, architectural aspects and determination of principal particulars as well as some other issues related to submarine specific features.

It is emphasised in the book that in our century of extensive use of computer aids for designing complicated engineering objects, and submarines undoubtedly refer to such objects, it is especially important for a designer to have a deep understanding of interrelation of submarine individual parameters and characteristics as well as an understanding of the intricacies of the submarine design process.

The authors hope that the book will be useful for everyone who dedicates their life to these most complicated but most interesting ships of the present time.

Authors express special thanks to Lidiya A.Krutitskaya, Anna B.Scorokhodova, Aleksei N.Umarov and Gennady D.Serditov.

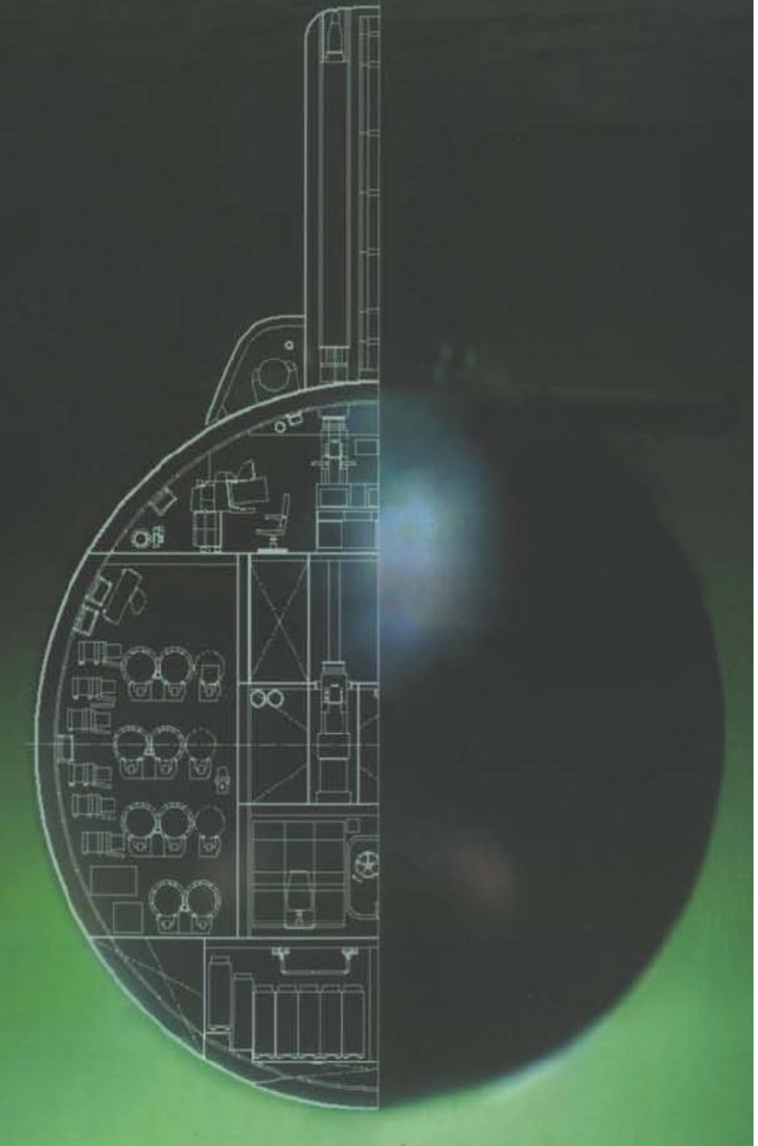


THEORY OF SUBMARINE DESIGN

Y.N. KORMILITSIN, O.A. KHALIZEV

Y. N. KORMILITSIN, O. A. KHALIZEV

THEORY OF
SUBMARINE DESIGN



Y. N. KORMILITSIN, O. A. KHALIZEV

THEORY OF
SUBMARINE DESIGN

2001

Yury Kormilitsin was born on 1 July 1932 in Khabarovsk, USSR. He spent his childhood in Vladivostok. In 1956 he graduated from the Leningrad Shipbuilding Institute.

Since 1956 he has worked in the CDB ME «Rubin» and has gradually risen from a design engineer of the Design Department to the post of the General Designer on conventional submarines and deepwater submersibles with non-nuclear power plants. He is State Prize Winner (1984 and 1998), a Doctor of Sciences (Engineering) and a Member of the St.Petersburg Engineering Academy. He has been the Chief Designer of four generations of diesel-electric submarines: Projects «Foxtrot», «Tango», «Kilo», «Amur» and their various modifications.

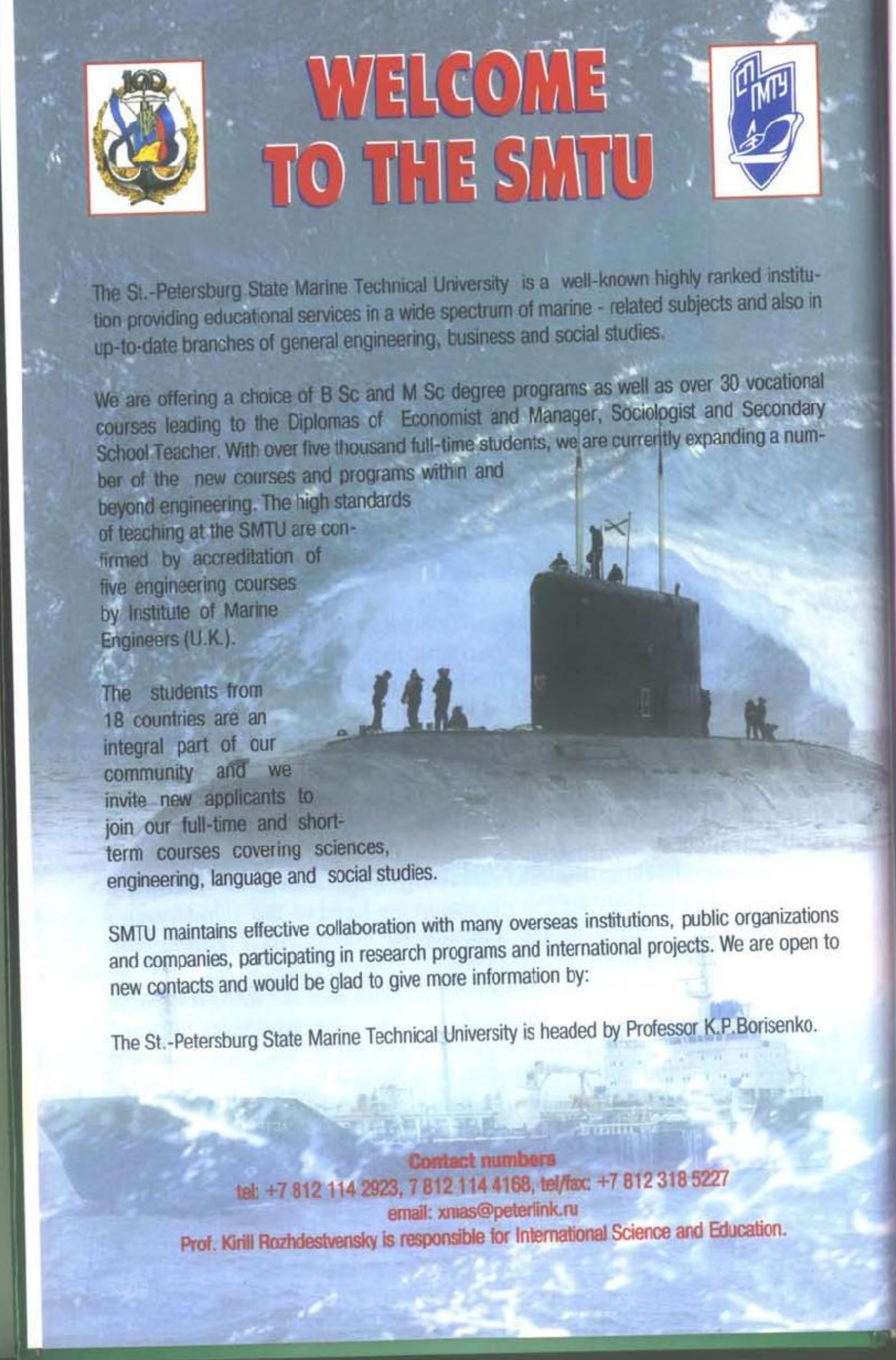
Yury Kormilitsin has developed and practically implemented a concept of submarine series development that is based on using a set of common architecture and arrangement features, ensuring continuously high combat efficiency throughout subsequent equipment and sensor upgrades at the least possible displacement and low acoustic signatures. He is the author of many engineering and design developments, scientific publications and inventions. He is a professor of the Ship Design Department of the St.Petersburg State Maritime Technical University.

Oleg Anatolievich Khalizev was born on November 18, 1944 in Kazan. He grew up in Leningrad and in 1970 graduated from the Naval Architecture Faculty of the Leningrad Shipbuilding Institute.

Since 1970 he has worked at the Ship Design Department of the Leningrad Shipbuilding Institute, the Faculty of Naval Architecture, starting as an engineer in a research team and gradually rising to the position of Professor of the Ship Design Department. He is a Master of Technical Sciences and since 1974 has been lecturing on problems of submarine and deepwater submersible designs to students attending major courses at the St.Petersburg State Maritime Technical University. Since 1987 he has also been the head of the «Underwater Shipbuilding» course at the Faculty of Naval Architecture and Offshore Engineering.

His scientific interests are associated with various design aspects of submarines and submersible vehicles. He has supervised a number of research projects in support of practical submarine design work.

Oleg Khalizev is the author of over 100 scientific publications and inventions, 19 textbooks and methodological instruction documents.



WELCOME TO THE SMTU

The St.-Petersburg State Marine Technical University is a well-known highly ranked institution providing educational services in a wide spectrum of marine - related subjects and also in up-to-date branches of general engineering, business and social studies.

We are offering a choice of B Sc and M Sc degree programs as well as over 30 vocational courses leading to the Diplomas of Economist and Manager, Sociologist and Secondary School Teacher. With over five thousand full-time students, we are currently expanding a number of the new courses and programs within and beyond engineering. The high standards of teaching at the SMTU are confirmed by accreditation of five engineering courses by Institute of Marine Engineers (U.K.).

The students from 18 countries are an integral part of our community and we invite new applicants to join our full-time and short-term courses covering sciences, engineering, language and social studies.

SMTU maintains effective collaboration with many overseas institutions, public organizations and companies, participating in research programs and international projects. We are open to new contacts and would be glad to give more information by:

The St.-Petersburg State Marine Technical University is headed by Professor K.P.Borisenko.

Contact numbers
tel: +7 812 114 2923, 7 812 114 4168, tel/fax: +7 812 318 5227
email: xmas@peterlink.ru
Prof. Kirill Rozhdestvensky is responsible for International Science and Education.

CONTENTS

4. **The Load Equation As a Function of the Displacement. Determination of the Displacement**

5. **Submarine Constant Buoyant Volume (CBV)**

6. **Submarine Trimming**

7. **Compensation of Submarine Variable Weights**

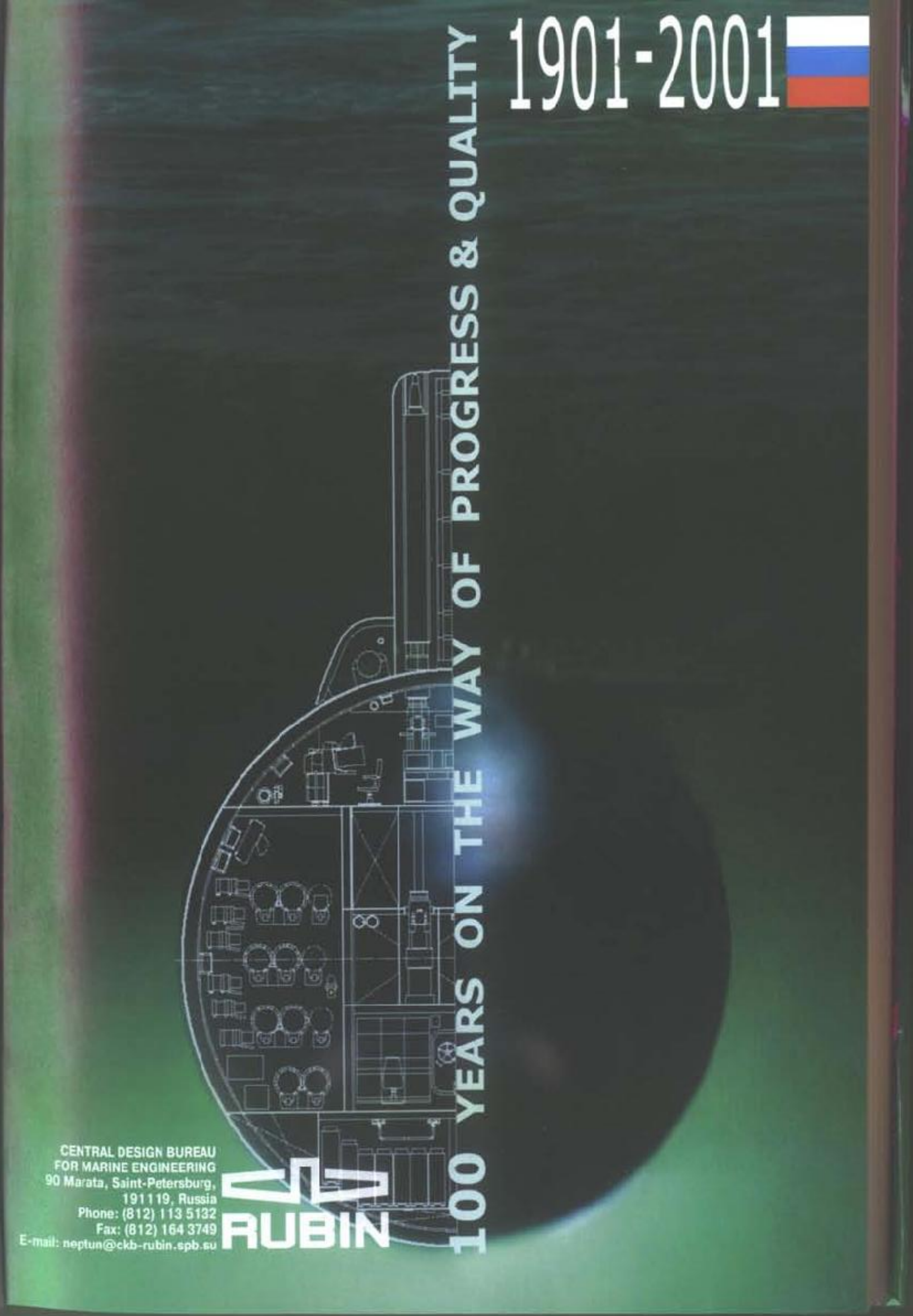
8. **Submarine Hullform Design**

9. **Determination of Submarine Principal Dimensions**

10. Submarine Lines Drawing

11. Design of Submarine Control Surfaces

12. Military-and-Economic Analysis and Its Role in Submarine Design



INTRODUCTION

The Evolution of the Submarine Design Theory

As with the situation with surface ships, we understand the submarine design theory as a scientific discipline that studies the creative process of producing a submarine and, first of all, evolving principal particulars of this submarine and justifying optimum design choices.

The physical meaning of some formulae of the basic ship design theory, like equations of mass, capacity and others, is as valid for submarines as for surface ships. Nevertheless, submarines are such specific engineering products that any direct transfer of surface ship analytical tools and techniques is, as a rule, unacceptable due to the very structure and physical essence of the involved relationships. Therefore, we believe that the submarine design theory has a right for independence and it should not be regarded as just a particular case of ship design theory.

The progress of underwater shipbuilding over the past 30 years has already resulted in its own diversification of design approaches. For example, there are distinctive specifics in design features of submersible vehicles, passenger submarines, etc.

The evolution of the submarine design general theory into an independent discipline started fairly recently and still is an on-going process.

Early developments in this field were initiated in 1939-1941 by B.M.Malinin [55], a prominent submarine designer and a professor of the Shipbuilding Institute. Based on evaluations of submarine designs, he identified individual groups of weights, which constitute the load, as functions of the displacement and other parameters of a submarine. Those formulae have enabled to use the weight (mass) equation for finding the displacement. He also derived approximate formulae for stability characteristics, the wetted area and other values suitable for initial design stages. In 1940 A.N.Shcheglov published a book titled «Design of Submarines» [92] that described methods for determining main dimensions and the displacement of submarines. In 1949 another publication appeared - «A Reference Book of Submarine Designer» - a two volume work edited by professor B.M.Malinin, summarising the experience of underwater shipbuilding in Russia from 1927 to 1945 [80]. In the same year S.A.Yegorov, Z.A. Deribin et al. completed their book on submarine design methods. Unfortunately, that work has never been published. They suggested a method to determine submarine displacement analytically by formulating and separately solving two separate equations: the equation of weight (mass) and the equation of buoyant volumes, and then to match the obtained results.

All those achievements had been based on pre-war experience of underwater shipbuilding. In 1950s the development of submarines with new structural and technical characteristics rendered a lot of earlier derived formulae inapplicable.

In 1952 A.N.Donchenko analysed weight loads of the first submarines built after the war and found new numerical coefficients, as well as new relationships between the displacement and individual components of the submarine load balance. It should be noted that since the 1950s various institutions (mainly of the Navy and of the Shipbuilding Ministry) performed a large number of studies associated with particular tasks at the nexus of the submarine design theory and other ship science disciplines. In this respect one should mention work by D.P.Skobov, L.V.Kalacheva, S.S.Zolotov, V.V.Rozhdestvenskiy in the field of submarine dynamics, Yu.A.Shemanskiy, N.S.Solomenko, V.T.Tomashevskiy in the field of submarine structural strength, A.A.Pravdin, M.K.Glozman, N.L.Sivers in the field of hull design, and many others.

It was during the same period that design theory issues reached textbooks. In 1954 there was a handbook by V.N.Kvasnikov and M.V.Saveliev [35] and in 1959 a textbook by K.P.Yefremov was published [31].

A considerable contribution to the development of the submarine design theory was made by professor S.A.Bazilevskiy [9]. In his scientific publications, as well as in lectures at the Naval Academy, he deliberated on techniques of submarine design aiming towards wider application of the similarity theory and error analysis.

Since the mid 1950s combat efficiency and capabilities of submarines have been continuously growing, as a result of the evolvement of new, more efficient means of maritime warfare. As submarines are fitted with more and more state-of-the-art tools of war, the number of possible design solutions becomes greater and greater. Under such conditions increasing numbers of design decisions have to be made at initial design stages when, based on evaluations of the efficiency of weapons, sensors and equipment, taking into account anticipated costs of developing and operating the submarine, they formulate design specifications. This stage of ship design is known as the Conceptual Design (CD). The CD development was stimulated by the progress of the submarine design theory in the direction of wider and deeper substantiation of the submarine design analytical arsenal and introduction of computers into CD procedures.

Among numerous studies aimed to support the Conceptual Design, one should note publications by L.B.Breslav, K.B.Malinin, N.N.Grigoriev, L.Yu.Khudiakov.

In the first of the above-mentioned investigations, the application of modern mathematical statistics methods has made it possible to refine the structure of approximate formulae for masses and volumes of the designed submarine. The second one considered various aspects associated with the use of analytical methods for generating tentative sketches of hull lines. The third one offered a method to find the normal displacement from masses and volumes, while the fourth of these publications dealt with methodological aspects of the Conceptual Design.

Crucially important for modern shipbuilding are military and economic evaluations of submarine designs. These issues happen to rest at the nexus of a whole bunch of sciences: design theory, tactics, economics, specific problems of mathematical analysis.

Many publications on such issues were made by L.B.Breslav [11], A.A.Narusbaev [58], I.G.Zakharov [66], L.Yu.Khudiakov [87] and some other authors.

As has been already mentioned above, the submarine design theory is closely related to other naval architecture disciplines: hydrodynamics, ship theory and structural mechanics, to construction technologies, economics and a number of other disciplines. The design theory extensively uses scientific tools of these disciplines for tasks associated with, for example, propulsive performance, manoeuvrability or strength of the designed submarine. However, here these tools are used in a different way and approached from different positions. This is due to the following specific features of design-oriented applications.

Firstly, unlike other disciplines, the design theory solves not direct but inverse tasks. For example, while ship theory calculations serve to determine the speed of an actual submarine, the aim of design efforts is to establish particulars of the designed submarine that would guarantee the desired speed.

Secondly, in contrast to all other disciplines that consider various abilities and parameters of the submarine individually, without relating them to each other, the submarine design theory can be characterised as a comprehensive system approach to the submarine as a single product in which everything is interrelated and interdependent. Therefore, it is necessary to consider how this or other decisions may influence not just a certain quality intended for improvement but the submarine as a whole, i.e. all other qualities and performances. Consequently it is not always that recommendations developed based on the submarine design theory agree with similar recommendations of other disciplines [14].

At the same time it should be mentioned that, in spite of the apparent multitude of investigations, the submarine design theory is not yet sufficiently fully developed even in such classical domains as design procedures. Relevant work performed by different agencies and organisations has not yet been truly systematised and generalised.

Evidently, international references contain virtually nothing on the submarine design theory. The only exceptions are a detailed publication [96] made in Great Britain that describes a number of particular problems of submarine design and a monograph [23] on general issues of ship design management.

1. SUBMARINE DESIGN MANAGEMENT AND METHODS

1.1. Submarine Design Management

Naval Force Development Programmes for certain periods of time are generated on the grounds of *long-term military-and-economic planning* that is itself based on forecasted national foreign-policy targets and tasks of military forces, particularly of the Navy, in achieving these goals. Other significant input comes from predictions of developments in weapons and other military hardware in both the subject and other countries.

Long-term military-and-economic planning is a hierarchic procedure performed at different levels, starting with the overall fleet configuration and going down to individual classes of ships. In particular, long-term military-and-economic plans should outline what types of submarines are to be constructed or designed within the considered period. The final result of these efforts is the Naval Force Development Programme that usually covers a period of about 10 years. Construction of any new type of a ship is included into such programmes only when initial design stages are already completed (usually after they have formulated and approved Submarine Design Specifications (SDS)). While being implemented, the programme may be corrected due to changes in the political situation, in production and economic resources and capabilities, in military equipment developments.

Naval long-term military-and-economic planning and programme development are performed using contributions from Navy Research Institutes, various organisations of the shipbuilding and other involved industries, Navy specialists and ship designers.

It is generally known that there is no way to design a sophisticated engineering product in one step. The process has to consist of several successive phases or stages of design efforts (Fig.1.1).

A flow chart of traditional phased submarine design process adopted in Russia [23] may be seen in Fig.1.1.

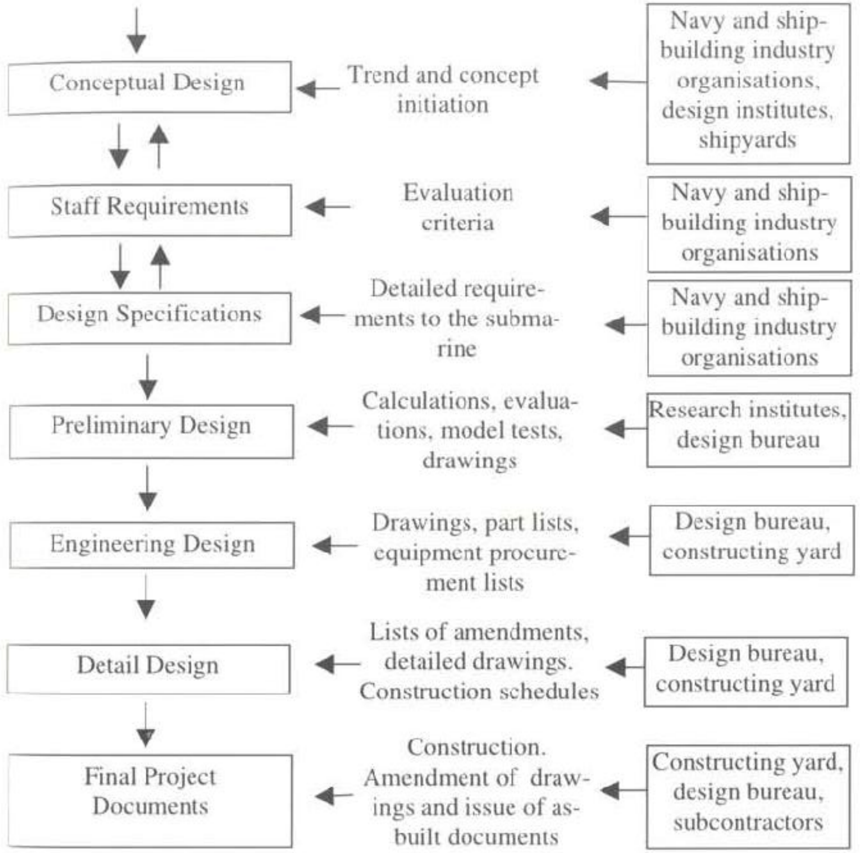


Fig.1.1. Design Phases

For the greater part of ships, submarines included, the design process starts with Conceptual Design which generalises the outcome of various research work relevant for design applications. Such studies are continuously carried out by advanced concept design teams from design and research establishments of both the shipbuilding industry and the Navy.

At this stage they investigate issues pertaining to the application of advanced equipment and weapon packages, new materials and design solutions for submarines; they evaluate effects of wide variations in tactical and technical particulars (e.g.: speed, diving depth, etc.), in the displacement and the architecture of submarines, perform feasibility studies in terms of cost and construction capabilities; investigate promising types of submarines. Conceptual Design is a multi-variant process involving extensive application of military-and-economic analysis in order to justify chosen decisions and utilising analytical methods to determine principal particulars of submarines.

With the start of a new Naval Construction Programme conceptual design efforts are re-directed to feasibility studies on the chosen types of submarines and formulation of requirements to their service and tactical characteristics. Actually, they often tend to see conceptual design as a comparatively narrow task and regard it as feasibility study and customer's requirements phase [87]. Conceptual Design is a synthesis of strategies and tactics of the Navy, of science and technology of shipbuilding and other involved industries.

The Staff Requirements (SR; Russian name: Operational and Tactical Assignment) are generated by the Naval Command and research organisations belonging to the Navy. This process also involves contributions from design bureaus of the shipbuilding industry.

In the Staff Requirements they:

– define the designation and missions of the submarine;

– specify and analyse data on the potential adversary, evaluate enemy countermeasures taking into account possible improvements in such capabilities, assess potential areas of combat operations, base locations and conditions, and availability of repair facilities, etc.

Based on the SR, they formulate Operational and Tactical Requirements that are tentative requirements of the Navy to configuration and main characteristics of the weapon package, protection features, endurance, speed, sea range, diving depth and seakeeping abilities of the future submarine.

The main goal of work on the SR is to evolve the most rational, in terms of both military and economic aspects, combination of tactical characteristics that would enable the submarine to fulfil the assigned missions in the best possible way.

In order to match tactical and technical features of the submarine and to make sure, in the first approximation, that they fit together, the Conceptual Design phase includes design studies on the subject submarine under rather wide variations of tactical inputs. For every considered variant they determine the displacement, main dimensions, the power plant capacity and the approximate construction cost. Several, so-called «basic», options are studied in greater detail, including making a sizeable bulk of calculations and drawings. Upon the completion of Conceptual Design work, they evaluate the efficiency of considered variants with the help of military–and–economic analysis methods. Then the variants are compared and the recommended version of the SR is submitted to the Naval Command for approval [75].

The generation of the Staff Requirements should, together with its supporting Conceptual Design efforts, be considered as an initial stage of the submarine design process.

Development of the Technical Proposal and Submarine Design Specifications (SDS).

The Technical Proposal for a submarine design (this design stage was earlier called «tentative» or «feasibility» design) is prepared by a design organisation from the shipbuilding industry based on the approved Staff Requirements. The aim of this design stage is to justify the advisability and to check the feasibility of creating a submarine to the approved SR.

Tasks to be solved during the development of the Technical Proposal may be grouped as follows:

– to check whether the SR fits available technical and economic capabilities; to find principal technical solutions necessary for achieving the specified tactical performances. For these purposes they carry out basic shipbuilding calculations required to determine submarine particulars, draw general arrangement plans, prepare an explanatory note; estimate submarine design, construction and operation costs;

– to find first-iteration solutions for administrative issues pertaining to the creation of the submarine, to compile lists of weapons and major equipment (power plant, machinery, instrumentation); to select manufacturers and suppliers of existing equipment, as well as organisations that will develop new equipment; to define the scope of research and development work necessary for developing new equipment and validating new technical solutions; to estimate time–frames for each stage of the submarine development project;

– to assess the technical level of the intended submarine from the point of view of national and international achievements in science and technology and to provide military and economic justifications for the project; to establish the number of such submarines required to achieve missions assigned to the Navy and to look into other issues of military–and–economic analysis. This group of tasks is as a rule assigned to research institutions of the Navy.

Essentially, the generation of the Technical Proposal may be considered to be the final stage of the Conceptual Design. It differs from the previous phase by a considerably smaller number of evaluated variants, but it involves a much greater scope of calculation and drawing work on each of the variants. At the Technical Proposal phase they mostly consider alternatives for key technical solutions, e.g., hull architectural type, propulsion plant type and other features affecting principal particulars of the intended submarine. This is the stage when they make first approximations of the displacement and main dimensions, as well as of other principal particulars of the submarine depending on alternative choices of the weapon package, the speed, etc.

Based on the solution of the above tasks, they select the optimum variant of the Technical Proposal and it serves as the basis for formulating Submarine Design Specifications (SDS; the Russian term is «Tactical and Technical Assignment»).

SDS set out detailed requirements of the customer (the Navy) for the intended submarine and usually contain the following data:

Designation of the submarine;

Weapons (missile, torpedo, mine) and sensors (sonar, radar, communication, computers, etc.);

Requirements for protection and stealth features (submarine signature intensity levels and platform noise affecting onboard sonar performance);

Platform features (tentative displacement, speed and sea range, diving depth, manoeuvring qualities, endurance, etc.);

Habitability conditions;

Extent of automation;

Power plant (type and key parameters);

Additional requirements set to the submarine in general or to some special features relevant for obtaining this or other additional quality.

Submarine Design Specifications are reviewed and approved by various authorities of the shipbuilding industry and of the Navy, and after their approval the project is included in the Naval Construction Programme.

Preliminary Design is based on the approved SDS and is actually the main design stage. While developing the Preliminary Design, it

is necessary to cover the following issues which determine whether the SDS implementation is practically feasible:

a) Determination of submarine displacement and main dimensions, as well as surface and submerged performance and manoeuvring qualities, speed and sea range;

b) Generation of block diagrams of systems and gears;

c) Resolution of issues associated with equipment arrangement in compartments and with the overall configuration of the submarine;

d) Selection of main machinery and major items of equipment;

e) Resolution of key issues of construction technology and management.

The Preliminary Design phase includes submarine model tank tests. Based on the outcome of these tests, the lines drawing of the submarine, hull appendages and propeller geometry are finalised.

They also carry out wind tunnel model tests in order to determine manoeuvrability characteristics of the submarine. During the Preliminary Design it may be found that it is impossible to meet certain SDS requirements. In this case specifications have to be reconciled. Preferably, the Preliminary Design should be as detailed as npossible to avoid any major changes at later design stages. The Preliminary Design package contains so-called «to-be-submitted» and «not-to-be-submitted» documents, as well as design data and documents from subcontractors [25]. The final scope of to-be-submitted documents, i.e. drawings, calculations, schematics and other technical documents, is established depending on the type and particulars of the subject submarine.

Engineering Design work is based on the approved Preliminary Design taking into account the changes and amendments introduced during its review and approval. Such adjustments should not imply changes in basic particulars of the subject submarine.

The aim of the Engineering Design stage is to make preparations for submarine construction, as well as for production and procurement of hull materials and equipment, weapons and sensors to be delivered by subcontractors. For this purpose they prepare sets of sufficiently detailed drawings, calculations and other technical documents. The Engineering Design work involves detailed consideration of all technical issues and should confirm tactical and technical features of the submarine. At the same time submarine construction specifications and part lists are compiled. The scope of to-be-submitted documents and the total scope of design work at this stage are approximately three times greater than at the Preliminary Design.

In order to optimise equipment and compartment-wise arrangements, General Arrangement drawings are made to a rather large scale (usually 1:10).

A special emphasis is placed at the Engineering Design stage on the construction technology that is developed so as to suit the actual shipyard, with regard to submarine construction schedules and financial aspects.

The Preliminary and the Engineering Design packages are reviewed and approved by the customer (the Navy) and shipbuilding industry authorities.

Detail (Workshop) Design. The main aim of this phase is to generate and issue the full set of detailed drawings of hull, mechanical and electromechanical components necessary for submarine construction. Accordingly, the main part of the Detail Design work is the generation of detailed drawings in numbers ranging from 6 to 10 thousands. Another crucial aspect of Detail Design efforts is the development of detailed construction technology. The Detail Design package also includes compartment-wise equipment installation (mounting) drawings, bills of materials, technical requirements and specifications for the subject submarine construction.

The Detail Design stage is completed with the issue of «to-be-executed» documents which are the Engineering Design documents corrected to comply with detailed drawings. E.g., there is a finalised record load calculation to check the position of the centre of gravity, etc. A large part of these documents are operating instructions for various equipment on the submarine.

Submarine Construction. During the construction the designer's functions are to perform daily supervision and monitoring of the construction progress to ensure that the yard meets design requirements (e.g., maintains the weight discipline) and to provide technical assistance to the shipyard. The designer's representatives participate in acceptance tests and trials of the submarine.

Preparation of As-built Documents. After the completion of the construction, the last stage of the designer's work is to produce as-built drawings and documents. The goal of this task is to provide the commissioned submarine, Naval bases, technical educational institutions and other relevant organisations with drawings and other technical documents that accurately describe the built submarine in terms of structures, equipment layout and all tactical and technical particulars and characteristics. The issue of as-built drawings and documents essentially means incorporation of corrections into the Detail Design package to cater for any deviations from detailed drawings made during construction and for actual values of tactical and technical performances measured during tests and trials of the lead submarine.

1.2. Submarine Design Methods

It is well known that the common approach to the design of sophisticated engineering products is the convergence method, often known internationally as the «trial-and-error method». This is to the full extent applicable to submarines. The essence of the method is that since it is impossible to reach the target in a single step, there should be several successive stages of design efforts (Fig.1.1).

At initial design stages the variation method is applied extensively. This method enables a solution to be found that would in the best possible way fit the designation assigned to the intended submarine.

Each step of the convergence method differs from the previous one by more complete and detailed substantiation of selected parameters, and more thorough deliberations on key tasks. Elements of the design are updated and supported by more accurate calculations. The scope of design documents grows and the number of drawings developed at every step becomes larger. The contents of documents under the same task titles also change step by step. Documents incorporate updated data on equipment and weaponry developed simultaneously with the submarine design. Accordingly, the scope of the load balance and constant buoyant volume (CBV) calculations at Preliminary and Detailed Design stages is quite different, calculation methods for various parameters and characteristics of the developed design respectively become more and more complicated.

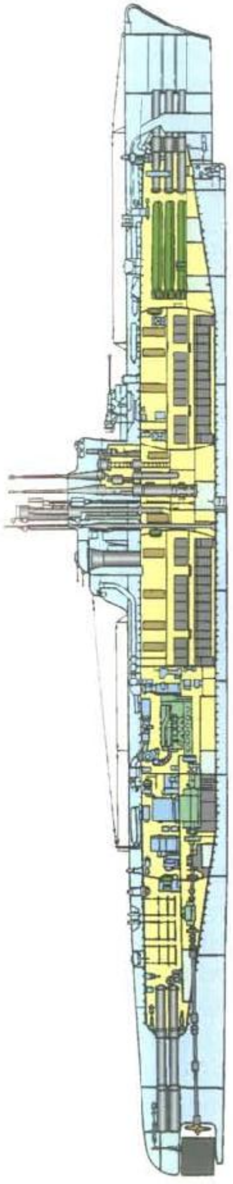
Under the convergence method they do not attempt to reconcile all parameters and particulars of the submarine at every step. Otherwise, it would overcomplicate both the preparation for construction and the design process itself, which are quite lengthy (from 3 to 10 years) [16]. Therefore, at certain design stages some parameters and characteristics should be preferably finalised and fixed. Normally, certain technical characteristics of the submarine adopted in the Preliminary Design should not drastically change at the Engineering Design stage. Among these characteristics are main dimensions, hullform, architecture and structural configuration of the submarine, although to a certain extent these parameters inevitably do undergo some changes.

The design phase sequence may vary depending on the Submarine Design Specifications and on how much the subject boat differs from previous ones. In real life there have been cases when a project started at the Engineering Design stage (e.g., Project 641 «FOXTROT» since it was largely a follow-on development and improvement of Project 611 «ZULU») (Figs.1.2 and 1.3) [43], [91], [95].

A crucially important design technique is the use of prototypes, i.e. data from earlier designs and statistic information about parameters and characteristics of already constructed submarines. However, utilising this approach one should keep in mind that for all practical purposes there is never a prototype that would fit all design requirements. This is obvious because the availability of such a prototype would render the new design meaningless.

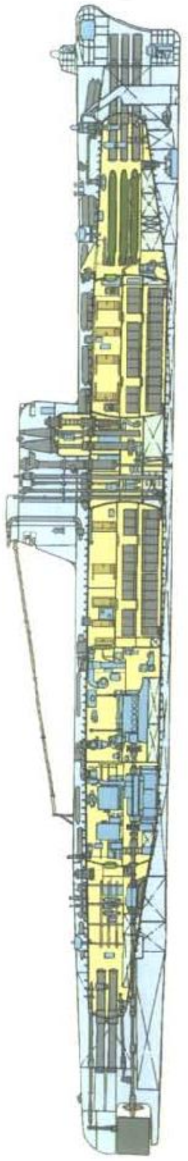
Nevertheless, the use of prototypes in the design of such complex things as submarines is both reasonable and necessary. The trick is that the very notion of «prototype» should be understood in broad terms. There may be several existing designs used as prototypes in the development of a new one. Thus, one of them may serve for hullform selection, another may be used for developing the general arrangement, the third one may help in calculations on strength, loads and volumes required for equipment layout, etc. Still, even using prototypes in this wide interpretation, it should be remembered that any prototype represents the past. Some time has already passed since its development, science and engineering have achieved new advances, and therefore the new submarine design should take into account the changes in requirements to design work introduced during the elapsed period.

In other words, data of the chosen prototype have to be corrected in a certain way. The same is applicable to statistic information. When using any statistical data in design work it is first of all necessary to be well aware of their origins, to know when, how and for what types of submarines those data have been obtained. At the same time it is necessary to remember that statistics and prototypes are nothing but experience accumulated over a given period of time. Developments in equipment and new materials, changes of requirements to design work, introduction of new structural configurations, new technological solutions – all these things influence various weights and volumes, parameters and characteristics.



Torpedo tubes	10
Torpedoes (calibre, mm)	22 (533)
Normal displacement, m^3	1831
Main dimensions, m:	
length overall	90.5
beam overall	7.5
Full surface speed, kn	17
Full submerged speed, kn	16
Submerged range at 2.1 kn, miles	440
Maximum diving depth, m	200
Endurance, days	75
Type of MPP	DEP
Full speed power, h.p. (r.p.m.)	3x2,000 (500)
diesel engines	1x2,700(540)
electric motors	2x1350 (440)
Shafts	3
Complement	72

Fig.1.2 Project 611 "ZULU" Submarine



Torpedo tubes	10
Torpedoes (calibre, mm)	22 (533)
Normal displacement, m^3	1952
Main dimensions, m: length overall beam overall	 91.3 7.5
Full surface speed, kn	16.8
Full submerged speed, kn	16
Submerged range at economic speed, miles	400
Maximum diving depth, m	280
Endurance, days	70
Type of MPP	DEP
Full speed power, h.p. (r.p.m.) diesel engines electric motors	3x2,000 (500) 1x2,700(540) 2x1350 (440)
Shafts	3
Complement	70

Fig.1.3 Project 641 "FOXTROT" Submarine

Further to the above, it should follow that utilisation of experience accumulated by previous generations of designers is justified and required, but it will help to successfully solve the specified task only if approached creatively [17].

Let us now consider specifically the early design stages, i.e. the Technical Proposal and the Submarine Design Specifications phases. In terms of creative work these stages are professionally the most attractive for designers and at the same time they are the most difficult ones since the designer has only a list of operational requirements and a clean sheet of paper to start with. At this stage almost everything is vague and uncertain. There are only ideas, some outlines of considerations that should be somehow implemented in the future design. Compared to other stages, at this point designing is an art rather than a science. The success to a large extent depends on the broad-mindedness and experience of the designer and the design team. An experienced designer familiar with many submarine projects may by applying various coefficients, weights and volumes at an early stage obtain rather accurate values for basic particulars of the new boat.

What methods can be used in submarine design at the very early stages?

Theoretically, all methods recommended by the ship design theory [6], [60], [61] are applicable. However, special features inherent to submarines to a large extent make the application of many of these methods quite difficult. These include the need for pressure and outer hulls to be arranged with respect to each other, the need for painstaking co-ordination of the load balance with the constant buoyant volume, the troubles of trimming under various service conditions – this is by far an incomplete list of submarine design specifics. Under such conditions even observing the law of Archimedes, which is Law No. 1 for submariners, is rather a complicated task. Besides, it should be kept in mind that unlike all other ships, space ones included, the submarine has to suffer numerous variations in external pressures from 1 to 100 atmospheres, and some special types even up to 1,000 atmospheres.

The early-stage choice of the submarine design method also depends on the nature of design specifications. Thus, in a case where the submarine is designed for an existing specified power plant, a specified package of weapons and sensors, it is somewhat easier for the designer since weights and sizes of at least some equipment are known from the very beginning. However, such specifications do not appear very often. Usually, the greater bulk of submarine components has yet to be selected and the designer has yet to optimise their numerous parameters: output power, weight, volume, consumed power, cooling requirements, etc.

All currently used methods are based on experience gained in the process of practical design work. Great contributions to the development of these design methods were made by well-known designers of the national submarine fleet: I.G.Bubnov, P.P.Pustyntsev, N.N.Isanin, B.M.Malinin, V.N.Peregudov, G.N.Chernyshov and many others [53]. In real life every school of designers prefers to use its own traditional methods for early-stage design work [82].

The Drawing or Graphic Method

Under this method the design work begins with graphic exercises on equipment arrangement in pressure hull compartments and a general study on the architectural outlook of the submarine. After that, based on the data of the graphic study, they perform first-approximation calculations on the load balance and the constant buoyant volume, and then check the boat trimming in terms of moments and forces. If the performed design study proves to be unsatisfactory from the point of view of these issues, it is modified and the results are checked again.

This method can be used, obviously, only when at the very beginning of the design the submarine equipment is defined (or specified), e.g., the main power plant and weights and dimensions of the larger part of other equipment items are known. This design method only allows for a limited number of options to be studied because the procedure is rather time-consuming.

Nevertheless, modern computers with suitable databases make this method quite promising.

The Graphoanalytical Method

The basic idea of this method is that to determine the displacement, main dimensions and other particulars of the submarine both graphic exercises and design formulae are used.

E.g., with the help of the mass equation they find the submarine displacement and select the power plant. Then they update the mass equation, re-calculate the displacement, make a graphic study on the arrangement of compartments and approximately estimate the reserve

of buoyancy. They also make the first approximation of the constant buoyant volume and evaluate submarine trimming. As a rule, they generate several equipment layout options. One should, however, remember that as long as the pressure hull is selected, the potential variety of alternative task solutions becomes limited. In some cases they may suggest several alternatives for the pressure hull too.

The Analytical Method

Contrary to both previous methods, this one is based not on graphic deliberations but exclusively on various analytical formulae. Thus, taking equations of mass, volume, stability, propulsion, etc., expressed as functions of target figures of the Submarine Design Specifications, displacement and other design parameters, one may solve these equations jointly and obtain the sought displacement, main dimensions and other submarine design values. The analytical method is widely used in Conceptual Design. It does not require labour-consuming graphic studies and enables a large number of alternative solutions for the given task to be considered. This method allows optimum task solutions based on a chosen set of criteria to be obtained. Obviously, the validity of these obtained results in many respects depends both on the chosen criteria and on variation ranges adopted for subject variables.

At the same time, the design quality depends as much on the designer's experience as on the designer's command of tools available from other disciplines relevant for submarine design purposes and on all achievements in other branches of science and engineering that may be utilised to enhance the quality of the design.

1.3. Computer Application in Submarine Design

A characteristic feature of modern submarine design is the ever-increasing utilisation of computer and graphic hardware.

Initially (1960–70's) computers were used just to perform the most standard ship theory calculations. Their procedures normally could be derived from «manual» calculation routines without any need significant modifications. These, primarily, included calculations of loads, ship statics and dynamics, strength of standard structures, etc. [39], [97].

However, the progress in computer hardware has stimulated further improvement of calculation methods, e.g., thanks to the opportunity to drop various simplifications and assumptions. New utility methods have rapidly found applications in design work, including the finite element method which made it possible to make more accurate predictions of stress fields, thus improving both the reliability of structures and material savings [81].

The domain of computer applications has expanded and covered new fields of engineering and design activities [61], [98].

At present, in addition to making the above-mentioned calculations, computers compile material bills, part lists, generate drawings, etc. First of all, computers are applied for the most time-consuming and routine jobs, they successfully cope with laying out equipment in compartments and with the preparation of general arrangement drawings. A real breakthrough is that computers are now assigned to find optimum solutions.

The goals and purposes of computer applications in design work, to a large extent, depend on the stage of the design development (Staff Requirements, Submarine Design Specifications, Technical Proposal, Preliminary, Engineering or Detail Design).

Thus, in the process of work on the Staff Requirements it is necessary to select and justify requirements for tactical and technical features of the submarine, to compile lists of major weapons, equipment, etc. The main aim of using computers at this stage is to find a combination of submarine characteristics that would enable the boat to fulfil the assigned tasks in the best possible way.

At the Technical Proposal stage, same as during initial steps of Preliminary Design work, the main task is to evolve the architectural and structural outlook of the submarine, to update the equipment and system package, to determine principal particulars like normal displacement, main dimensions, manoeuvring characteristics, etc.

At these stages the task of computers is not just to determine some particulars but to optimise submarine particulars and the whole configuration aiming, e.g., at the least normal displacement or the lowest cost to satisfy SDS requirements.

During the later stages the design work becomes much more labour-consuming. This happens due to the geometric–progression growth of the amount of information that needs to be recorded, corrected and used or relayed to other departments of the design bureau. Considering that all design documents must be perfectly co-ordinated, it is irrational to do all this work manually because of both the huge labour and time costs and because of unavoidable errors associated with the human factor. In this task the computer is indispensable but its function becomes different: to reduce human labour content and to enhance design work quality.

In this respect it is most interesting to consider early design stages because they involve extensive application of design theory methods to get practical results.

Computerisation of the design process for any kind of engineering products, including submarines, assumes the availability of a mathematical model and corresponding software implementing the algorithm of that model.

Let us formulate a submarine design task as an extremum problem. Let C $(C_i \ldots C_j)$ be the vector of SDS targets, data from prototypes, etc. (e.g., diving depth, speed).

Vector X $(X_i \ldots X_n)$ is the vector of variables to be optimised, i.e. submarine particulars (displacement, main dimensions).

The vector X components are restricted from both sides as:

$$(X_i)_{min} \geq X_i \leq (X_i)_{max},\ i=1 \ldots n \tag{1.1}$$

These constraints follow, e.g., from service and construction limitations.

Requirements to the submarine are formulated as:

$$B_j(X,C) \oplus A_j(C),\ j=1 \ldots m \tag{1.2}$$

where B_j is an estimation of the j-th quality of the subject design variant;

$\oplus$ is the relator (>, <, etc.); A_j (C) are requirements to the j-th quality.

In this case any variant (any set of ï) that satisfies (1.1) and (1.2), is acceptable.

To select the best variant, we need to introduce the efficiency criterion, i.e. an index of design perfection:

$$Z(X, C) \rightarrow extr \tag{1.3}$$

It is assumed that Z (X, C) is a steady function of the design quality.

Thus, the task of submarine design is to find out such an X vector with which criterion (1.3) reaches extreme values at known C and satisfied (1.1) and (1.2).

A submarine mathematical model representing the totality of functions B_j A_j and ё is shown in Fig.1.4 [82].

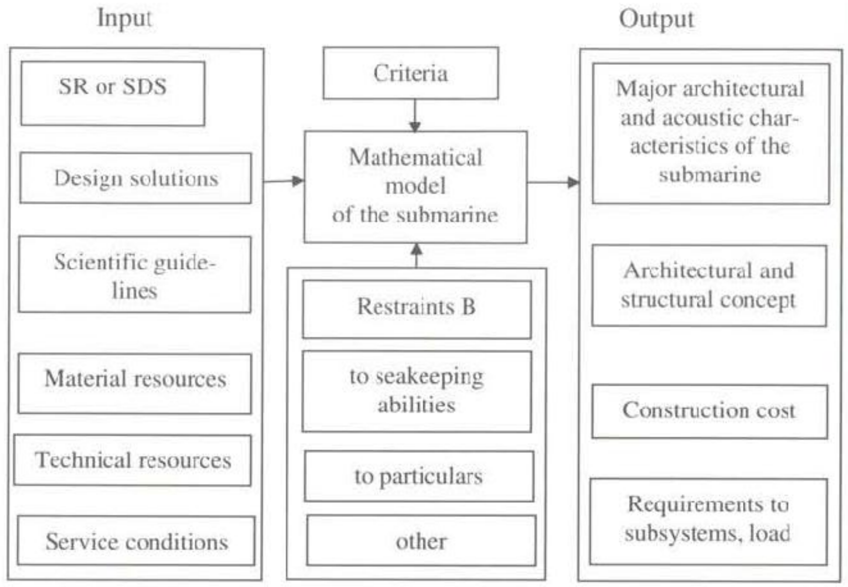


Fig. 1.4 Mathematical Model of a Submarine

The main requirement to any submarine mathematical model is its adequacy, i.e. theoretical solutions obtained by means of this model should be validated by available practical data.

This is achieved by:

– generating the submarine geometrical model allowing it to describe different shapes of the outer and the pressure hulls, as well as of the appendages;

– developing algorithms representing the physical essence of the described relationships, as well as algorithms based on calculation procedures;

– increasing the extent of detailing of the mathematical description of the design process;

– using direct calculation methods of naval architecture.

Mathematical models used in design bureaus are developed mainly for the sake of solving the following design tasks:

– assessments of practical achievability of targets set by the customer, checks of compatibility and consistency of these requirements, justification of submarine characteristics outlined in design specifications;

– determination (updating) of principal particulars of the submarine, of the architectural and structural concept.

The first task is relevant mostly to the Technical Proposal stage (Fig.1.5) and includes generation of different variants of the submarine, evaluation of their particulars and characteristics, and selection of the preferable variant for the future design work.

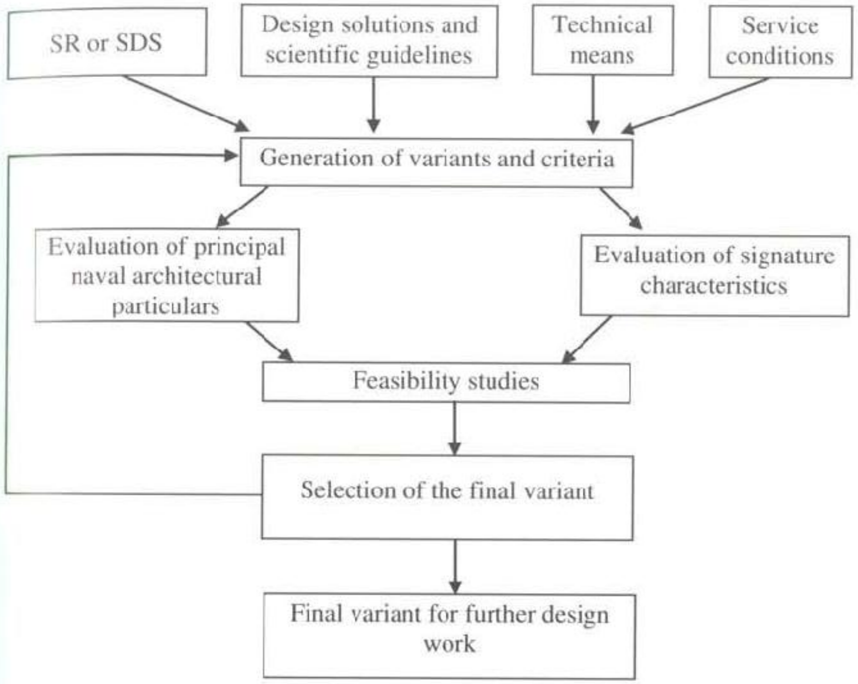


Fig. 1.5. The Traditional Task Solution Flowchart of the Technical Proposal Stage

Fig.1.6 shows a possible configuration of a computer-aided design (CAD) system intended for the problems of the first type.

The second task logically follows from the first one. At this stage they refine the description of the outer and the pressure hulls, update the arrangement, perform calculations on submarine statics and dynamics, and prepare information for further analysis by other departments.

At the same time it should be noted that although a computer is a powerful tool with many abilities, it is only a tool in the hands of a designer and enables the latter to solve specified tasks faster, in more depth and in a broader sense. Just so. The results obtained with computer assistance largely depend on how well the designer understands the physical basis of this or other phenomenon and can analyse the obtained results.

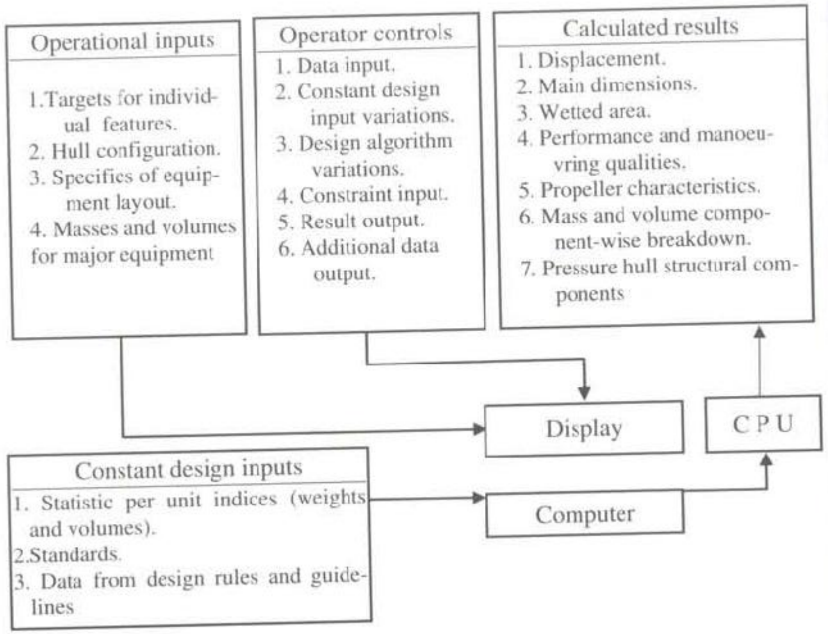
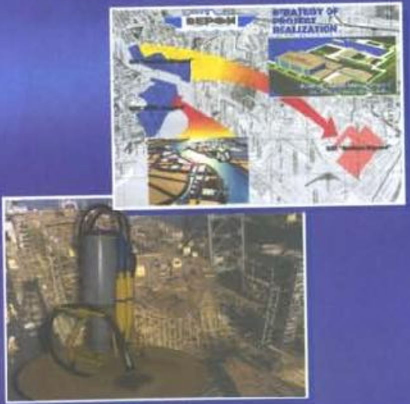


Fig. 1.6. An example of CAD system architecture

This is an appropriate point to mention that any design work, including that for the most sophisticated products like submarines, is an art. The designer should possess and continuously improve his skills and knowledge, perfecting them through hand drawing and analysis, never trusting the baby solely to a machine [50].



2. SUBMARINE DISPLACEMENT

2.1. Submarine Displacement Types

Unlike for surface ships, for submarines there is only one natural load condition: the normal load. The reason is that in accordance with the law of Archimedes the submarine weight has to be equal to the submerged buoyancy while the latter is definitely dictated (at water specific weight $\gamma = \rho g = \text{const}$) by the submerged constant buoyant volume.

By «normal load» we understand the total weight and the position of the centre of gravity of a completely outfitted submarine with the complement, machinery, systems and gears fully ready for operation, with issued special-purpose equipment and normal stocks of consumables (fuel, water, provisions, etc.) and trimmed with solid ballast [74].

The submarine normal load corresponds to the normal displacement D_0. The normal displacement is equal to the product of the design water density into the volume displacement. The notion of constant buoyant volume V_0 is used when considering the submerged submarine; for the surface condition they apply volume displacement V_{SFB} that corresponds to the full-buoyancy waterline. These two volumes are equal in value but formulated differently.

$$D_0 = \rho g V_0 \quad D_0 = \rho g V_{SFB} \qquad (2.1)$$

In underwater shipbuilding they also use several other displacement notions that are necessary to account for the weight of the water flooding hull volumes that are not included into the constant buoyant volume (CBV): those of the main ballast tanks (MBT) V_{MBT} and of the permeable structures V_{MBT}.

Submerged displacements D_S and V_S take into account the weight and the volume of water in the net MBT volume.

Submerged displacements D_S and V_S represent the total watertight volume that remains watertight until the submarine dives.

$$D_S = D_0 + \rho g \sum V_{MBT}$$

$$V_S = V_0 + \sum V_{MBT} = V_0 \cdot (1+\varepsilon) \qquad (2.2)$$

where $\varepsilon = \dfrac{\sum V_{MBT}}{V_0}$ – is the relative buoyancy reserve.

The total submerged displacements D_{FS} and V_{FS} include the weight and the volume of water in MBT and in all permeable parts of the hull.

$$D_{FS} = D_0 + \rho g \sum V_{MBT} + \rho g \sum V_{PEP}$$

$$V_{FS} = V_0 + \sum V_{MBT} + \sum V_{PEP} \qquad (2.3)$$

The total submerged volume is calculated by the outer surface of the hull plating including volumes of all appendages. It should also include any external coating applied to the hull.

The greater part of V_{FS} is the bare hull volume V_{BH} calculated from the moulded surface (ignoring plate thickness, external coating on the outer hull and appendages).

The above-listed displacement notions are applicable to any floating underwater object.

Diesel-electric submarines can take extra fuel capacity into specially fitted fuel-ballast tanks. In order for the submarine to stay submerged, the residual positive buoyancy of the fuel has to be balanced by an adequate amount of additional stocks (oil, water, provisions) and water in auxiliary ballast tanks (ΔP). For the case of sailing with extra fuel, they use the notion of «displacement with excessive fuel capacity» D_{EC}, V_{EC} found as:

$$D_{EC} = D_0 + \rho_F g \sum V_{FBT} + \Delta P = D_0 + \rho g \sum V_{FBT}$$

$$V_{EC} = V_0 + \sum V_{FBT} \qquad (2.4)$$

where V_{FBT} is the net volume of fuel-ballast tanks.

From formulae (2.4) one may see that all these displacements are modifications of the normal displacement as in every case we just extend the «added weight» method, which is commonly used in naval architecture, to some flooded volumes of the hull.

Each of the above-listed displacement notions has a certain physical meaning and is applied within its own range of tasks. Thus, the normal displacement determines the submarine weight in air without water in MBTs and permeable structures. Derivatives of this displacement are used in tasks associated with construction technologies, submarine transportation, and in economic calculations (launching weight, transported weight). Actually, it is the normal displacement that they usually state in SDS.

The normal displacement is a basic, initial parameter. Nevertheless, it is not what defines the hullform, the main dimensions or such major submarine particulars like surface and submerged performance and manoeuvrability. These qualities respectively govern the surface and the total submerged displacements because only they are characteristics of the hullform, main dimensions, total moving weight and wetted surface of the submarine. This is one of the major specific features of submarine design. Considering the above, as well as the fact that signature levels depend on the total submerged displacement, when ordering a submarine it should be reasonable to specify requirements to this particular displacement.

2.2. Displacement (Load) Breakdown into Standard Groups

In order to properly manage load calculations, to reduce the probability of errors, as well as to make it possible to compare loads of different submarine designs (prototypes) and utilise such data in design work, load balance calculation results should be presented in a uniform format. Therefore, load calculations for submarines, same as for surface ships, are regulated by relevant industrial standards that contain some general rules for calculations, define the breakdown of component weights constituting the submarine load and the format of load balance calculation result tables.

All weights collectively constituting the normal weight load of the submarine are broken down into groups, subgroups and types. A numeral code is assigned to each weight. Weight groups and group codes correspond to the «Classifier of the Unified Design Document System, Class 36 (ships, ship equipment)» [33] following which they generate submarine detailed drawings at the Detail Design stage.

Table 2.1 demonstrates the format for logging load balance components.

Depending on the design stage, the submarine load balance is calculated with different extents of detailing and with different methods. For the Technical Proposal, loads are usually subdivided only into groups while at the Preliminary Design phase they are further segregated into subgroups. In such cases weights are mostly re-calculated from prototypes using approximate formulae, or are determined based on some steady statistic regularities derived from the analysis of loads of earlier constructed or designed submarines. Generally, the accuracy of load and displacement component calculations with these methods is not high (about 10%) because initial data may vary within wide ranges. At the later design stages, when they need higher accuracy, the use of such methods becomes very limited.

Table 2.1

Tabular Log for Load Calculation Results

Load component code	Load component description	P, t	Levers			Moments			Notes
			X, m	Y, m	Z, m	Mx, tm	My, tm	Mz, tm	

At the Engineering Design phase the load is broken down into subgroups and components. Weights and levers are determined more accurately due to the more detailed weight breakdown and rather detailed structural and general arrangement drawings, system and electrical equipment schematics, etc.

At the Detail Design stage weights and levers are calculated based on detailed drawings, more detailed general arrangement drawings and specifications for subcontracted equipment.

As a result of these efforts the so-called record load balance (as calculated from detailed drawings) is issued.

In addition to levers and moments in terms of the height above the base plane and the distance from the midship section, at Engineering and Detail Design stages they calculate moments of weight with respect to the centreplane in order to make sure that there is no static heel and, if necessary, to eliminate it by structural modifications or ballast.

The load balance calculation should contain a clear indication of the abscissa reference plane position with respect to the nearest actual frame and a table of frame offsets from this reference plane.

Table 2.2 shows the standard breakdown of submarine weights into groups [16], [33], [65], [69].

The standard weight breakdown is a convenient tool both for load calculations while generating submarine drawings and for weight management during construction.

Table 2.2

Submarine Load Component Groups

Group Number	Description	Diesel-electric submarines	Nuclear torpedo submarines	Nuclear missile submarines
000	Displacement margin	0.5-1.5	1.0-1.5	1.0-1.5
100	Hull	37-38	38-39	39-40
200	Hull gears, fittings	3-4	3-4	2-3
300	Furniture and equipment of spaces, paint, insulation, special coatings, protectors, spare parts and supplies	8	6-7	6.5-7.5
400	Mechanical equipment, pipelines and systems of power plants	8-9	16-18	13-14
500	Hull systems	8.0-8.5	8.0-8.5	6-7
600	Electric equipment and cables of electric power systems, electric networks and radioelectronic equipment	16-20	7-8	6-8
700	Weapons and their supporting systems	4-5	5	11-16
800	Stocks and complement	3-5	4-5	2-3
	Total per load groups without ballast	88.5-99.0	88-96	87-100
	Solid ballast			
	Normal load of the submarine at ρ = t/m^3			

In conceptual design, when basic particulars of the boat are yet to be determined, one may notice certain drawbacks of this standard breakdown because its groups combine weights dictated by different characteristics and particulars of the submarine.

In this regard it is necessary to make an important comment. Since the appearance of computers their abilities are widely used for calculating all load components: weights, moments and their sums. This is absolutely natural. However, if, especially at early stages, designers neglect «manual» and comparative checks of weight and moment calculations, mistakes are inevitable and their results may be deplorable.

2.3. Load Breakdown at Early Design Stages. Weight Indices

The equation of weights, which determines the displacement of a submarine, can be solved only when relationships between load components and submarine characteristics and particulars are already established. Therefore, at early design stages the weight breakdown differs from the procedure prescribed by the standard.

First, they segregate those submarine component weights that can be derived accurately enough from the data of design specifications. These include weights of weapons, stocks, complement, power plants, etc.

Secondly, all other weights are grouped according to the degree of their dependence on principal characteristics and yet unknown particulars of the submarine.

This load breakdown approach (let us for the sake of convenience call it «design» principle) allows to rather accurately calculate, even at early design stages, all specified weights and to establish for the rest of the weights some more obvious physical relationships than those implied in the standard [74].

Let us see how submarine load groups change when we apply the design breakdown instead of the standard one.

First of all we put together all structures subjected to the full external pressure: the pressure hull proper (plates, frames, stiffeners) and equistrong structures (end bulkheads, the sail, pressure tanks, etc.). Let us designate these weights as P_{PH} and P_{EST}.

The rest of the standard Group 100 «Hull» components become a new category called «Light Hull» P_{LH}. When we need more accurate calculations, this item can be further subdivided into a number of sub-items.

Submarine hull systems and gears (Groups 200 and 500) are combined under a single title P_{GS}, though, similarly to P_{LH}, they can be calculated more accurately.

In Group 300, it is advisable to segregate «Coatings» P_{COAT} as their weight is determined, mostly, by signature control requirements and can be calculated separately.

In diesel-electric submarine (SSDE) design, Group 400 as a rule consists of the following items:

- diesel plant P_{DP},
- electric propulsion plant P_{EPM},
- shafting P_{SH} with associated auxiliary machinery and gears.

For a nuclear submarine (SSN), this group consists of the main power plant P_{MPP} and the auxiliary power plant P_{APP}.

It is advisable to represent Group 600 as three items:

- storage battery system P_{SB},
- general-purpose electric equipment and cables P_{EEG};
- radioelectronic aids P_{REA}.

For nuclear submarines, P_{SB} may be considered together with the weight of the main power plant.

Group 800 should be split into:

- fuel and oils P_{FO};
- complement provision and fresh water stocks P_{SCR};
- transported weights P_{TRC};
- trimming and trapped water P_{TTW}.

Group 000 covers reserves of displacement left for future upgrading P_{UDM} and for design and construction of the submarine P_{CDM}. The solid ballast P_{BAL} is presented as a separate item.

Depending on special features of the subject submarine, on the scope of initial data inputs and on the availability of a close prototype, this design load breakdown may be modified. In particular, it may be made more detailed or, vice verse, more general. Sometimes it may be more convenient to group weights by similar designations or by submarine weight modules.

Formulae in which weight indices are used for approximate estimations of submarine weights may be divided into two groups.

The first group: weights are presented as functions of those characteristics and principal particulars of the submarine that determine her geometric configuration

$$P_i = p_i f_i(D_{FS}, L, B, H, \delta \ldots \vartheta, H_{LIM}, R) \qquad (2.5)$$

where p_i – weight index of the 1st group;
f_i – functions of principal particulars;
L – hull length;
B – hull breadth;
H – midship hull height;
δ – block coefficient;
ϑ – submarine speed;
H_{LIM} – maximum diving depth;
R – sea range under subject conditions (surface, snorkel, submerged).

Similar functions are commonly used in the design of surface ships and vessels. It is more difficult to use such formulae in submarine design because weight calculations are made for the normal displacement that does not determine the main dimensions and the outer hullform. The relationship between D_0 and D_{FS}, as will be shown below, is not very stable even within any single architectural type of submarine, and the use of D_{FS} in formulae for weight estimations leads to higher errors. Therefore, weight estimation relationships of the first group are, in submarine design, usually formulated like:

$$P_i = p_i f_i(D_0, \vartheta_1, H_{LIM}, R \ldots) \qquad (2.6)$$

The second group of formulae serves to find weights of individual structures from their known dimensions or volumes

$$P_i = g_i \varphi_i(V_i, l_i, b_i, h_i \ldots) \qquad (2.7)$$

where g_i – weight index of the 2nd group;
φ_i – functions of characteristic dimensions of the subject structure;
V_i – volume of the subject structure;
l_i, b_i, h_i – length, breadth and height of the subject structure.

Formulae of the second group are used for more detailed calculations when the general arrangement schematics are already available but strength calculations and detailed drawings of structures have yet to be made.

Weight indices may be derived from the following documents:

- documents of prototype submarine designs (one or several);
- documents of submarine designs for which load calculations have been made in sufficient detail;
- subcontractors' documents from which it is possible to find, e.g., weight indices of the power plant, electrical equipment, etc.;
- special design studies made as preliminary feasibility checks for some new design solutions suggested for the submarine;
- predicted weight indices assumed in the Conceptual Design based on the analysis of future engineering developments.

In practical design tasks it is crucial to select weight indices corresponding to the level of the considered task.

When we calculate the weight of a whole group, we should apply weight indices derived for this entire load group; if we consider a subgroup weight, we should use subgroup weight indices; and finally, when we come to the weight of an individual structure, we should apply weight indices computed from a characteristic dimension or parameter of that very structure.

We should, however, note that while using weight indices or other values derived from above-mentioned documents, the designer has to remember that any direct transfer of these data to a newly designed submarine may turn into just a way to conserve the technical level of the prototype. Therefore, the application of weight indices and documents of prototype designs should be preceded by creative analysis and corrections for the latest engineering achievements and special features of the subject design.

3. WEIGHTS OF INDIVIDUAL GROUPS AND LOAD ITEMS AS FUCTIONS OF PRINCIPAL CHARACTERISTICS OF THE SUBMARINE

3.1. The «Hull» Load Group

There are a number of formulae for the weight of surface ship hulls. These formulae relate the weight to the ship displacement and main dimensions, including the hull depth and the block coefficient.

It is impossible to use these formulae for submarines for two reasons:

– first, submarine main dimensions are determined exclusively by the total submerged displacement;

– secondly, there are two hulls (pressure and light) with their separate functions. Therefore, in weight calculations for the «Hull» group we have to consider these hulls separately.

Pressure Hull and Equistrong Structures

The Pressure Hull Weight P_{PH} depends on the design pressure (diving depth), geometrical characteristics, physical and mechanical properties of material. Besides, it depends on the structural features, e.g., the framing system (internal or external), on the chosen frame spacing, on rules and procedures applied to structural strength analysis [1], [64], [77], [90].

At the stage when principal particulars of the submarine are being determined, when dimensions of pressure hull (PH) compartments are not yet established, compartment weights are estimated with elementary formulae:

$$P_{PH} = p_{PH} D_0 \tag{3.1}$$

$$P_{PH} = g_{PH} V_{PH}, \tag{3.2}$$

where V_{PH} – the PH moulded volume as measured on the internal surface of the plating.

Formula (3.1) may be used to estimate submarine displacement. It represents the simplest (and at the same time the least accurate) relationship between the PH weight and the submarine displacement. The P_{PH} index (the PH relative weight), same as all other indices of this kind, is dimensionless.

Formula (3.2) is used at the early design stages quite widely. It includes the dimensional index g_{PH} (t/m^3) sometimes called «specific weight of the PH», that shows the weight per 1 m^3 of the buoyant volume provided by the PH. This index has a definite physical meaning. The difference

$$\eta_{PH} = \rho - g_{PH} \tag{3.3}$$

may be regarded as an efficiency index of the pressure hull as a source of buoyancy. The η_{PH} value determines what payload can be accommodated by the PH per 1 m^3 of its volume.

Comparing formulae (3.1) and (3.2) we can derive a formula to relate indices P_{PH} and g_{PH}. It shows that index

$$P_{PH} = g_{PH} \frac{1}{\rho} \left(\frac{V_{PH}}{V_0}\right) \tag{3.4}$$

should be less steady as it depends on g_{PH} and on $\left(\frac{V_{PH}}{V_0}\right)$, which, as will be described below, may vary within rather a wide range. Thus, e.g., at the same value $g_{PH} = 0.18$ t/m^3 the PH relative weight varies within $P_{PH} = 0.13$ to 0.17.

Let us consider the same aspects associated with practical application of (3.2).

To escape effects of individual features of any actual submarine PH configuration, which is usually a combination of cylindrical and tapered components, let us introduce an arbitrary analogue of the pressure hull: a cylinder with a constant radius along the entire length, stiffened by equirigid frames without any cutouts or local reinforcements. This «analogue cylinder» has the same as the real PH volume and length, is built of a material of the same grade and designed to the same external load using the same calculation procedure (Fig.3.1)

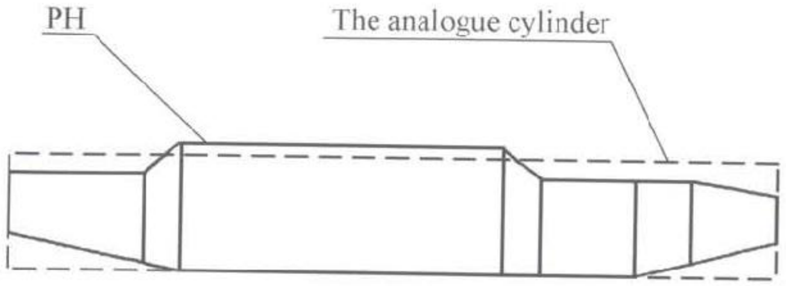


Fig. 3.1. The Pressure Hull Analogue Schematic

Let us call the combined weight of plates and frames of this analogue cylinder the «theoretical weight» of the PH

$$P^{T}_{PH} = g^{T}_{PH} V_{PH}$$

where g^{T}_{PH} – the PH theoretical weight index.

In order to be able to consider the weight of the actual hull, let us introduce two static coefficients k_{SSR} and k_{LSR}:

$$P_{PH} = k_{SSR} \cdot k_{LSR} \cdot g^{T}_{PH} V_{PH} \qquad (3.5)$$

Coefficient k_{SSR} accounts for the fact that the real hull has small distributed stiffeners and reinforcements for plating, framing and tapered portions while some plates have cutouts and some parts of PH frames are removed where they would have crossed pressure tanks (PT) equistrong with the pressure hull. If the value of the index found from the specified thickness of the plating and volumes of equistrong tanks is 2 to 3% of D_0, this coefficient is $k_{SSR} \approx 1.02$ to 1.04.

Coefficient $k_{LSR} = 1.05$ to 1.22 accounts for large concentrated reinforcements: bossings of propeller shafts, coamings of missile silos, etc. and is re-calculated from a prototype sufficiently close in terms of the type and scope of hull reinforcements.

Comparing (3.2) and (3.5) we can find a relation between indices of the actual and the theoretical PH weights.

$$g_{PH} = k_{LSR} k_{SSR} g^{T}_{PH} \qquad (3.6)$$

Since the real submarine PH is quite close to the analogue cylinder and the factors determining their weights are identical, we may investigate these factors using the g^{T}_{PH} index as an example.

The general functional dependence for g^{T}_{PH} can be formulated as:

$$g^{T}_{PH} = f(P_D, \rho_{PH}, \sigma_T, E, d_{PH}, \ell_{COM} \ldots) \qquad (3.7)$$

where: P_D – design load;
ρ_{PH} – hull material density;
σ_T – hull material yield strength;
E – modulus of elasticity;
d_{PH} – PH diameter;
ℓ_{COM} – PH compartment length.

For the analogue cylinder the g^{T}_{PH} index can be determined from a single frame spacing (Fig.3.2).

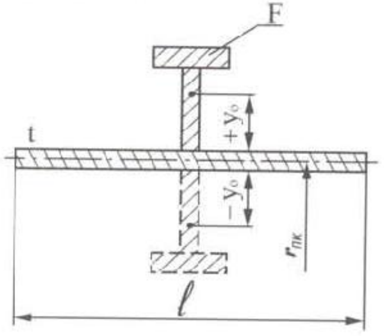


Fig. 3.2 The Frame Spacing Design Model.

$$g^{T}_{PH} = \frac{P^{T}_{PH}}{V_{PH}} = \frac{P_{PL} + P_{FR}}{V_{PH}} = \frac{2\pi r_{PH} t \ell \rho_{PH} + 2\pi (r \pm y_0) F \rho_{PH}}{\pi r^{2}_{PH} \ell}$$

After relevant manipulations we arrive at:

$$g^{T}_{PH} = 2\rho_{PH} \frac{t + \frac{F}{\ell}(1 \pm \frac{y_0}{r_{PH}})}{r_{PH}} = 2\rho_{PH} \frac{t_{RFT}}{r_{PH}} \qquad (3.8)$$

where: t – PH plating thickness;
ℓ – frame spacing;
F – frame area;
y_0 – offset of the frame section neutral axis («+» for external frames);
t_{RPT} – reduced plating thickness.

Let us expand the g^{T}_{PH} index formula (3.7) into functions of governing parameters.

Structural particulars of the PH (t, F and ℓ) in formula (3.8) are determined by PH strength analysis in terms of stresses and buckling resistance of plates and frames. It is rather difficult to obtain a sufficiently accurate analytical expression for the g^T_{PH} index that would account for all conditions of PH calculations, even for such a simplistic structure like a stiffened cylinder. Assuming that the plate thickness is determined based only on the strength considerations, we can re-calculate g^T_{PH} from a prototype with the same grade of material:

$$g^T_{PH} = g^T_{PH} \frac{H_{LIM}}{H_{LIM_0}} \cdot \frac{\sigma_{T_0}}{\sigma_T} \qquad (3.9)$$

where H_{LIM_0} – extreme diving depth for the chosen prototype submarine;

σ_{T_0} – prototype hull material yield strength.

This formula can be used for a fast approximate evaluation of the PH weight index at different H_{LIM} and σ_T when their variations are small because the neglect of buckling conditions and other assumptions may lead to considerable errors. Therefore, they use results of systematic strength calculations for circular cylinders simulating submarine pressure hulls with variations of initial data: the material (ρ_{PH}, σ_T and E), the design load (P_D), the PH geometry (r_{PH} and ℓ_{COM}). Values of g^T_{PH} obtained by such calculations are plotted as curves.

Let us consider the effects of geometric parameters: the PH diameter d_{PH} and the compartment length ℓ_{COM} upon g_{PH}.

The diving depth and the material grade will be assumed to be invariable.

Under a strict task formulation, for the sake of result definiteness with every variant of d_{PH} and ℓ_{COM} we should look for such a combination of t, F, ℓ that would minimise g^T_{PH}, i.e. would show the least PH weight.

In Fig. 3.3 one can see plots of the following functions:

$$(g^T_{PH})\min = f_1(d_{PH}, \ell_{COM} = \text{const})$$
$$(g^T_{PH})\min = f_2(d_{PH}, \ell_{COM}/d_{PH} = \text{const}) \qquad (3.9)$$

In the first case g^T_{PH} considerably decreases with the growth of d_{PH}. This is explained by the increasing effect of bulkheads becoming relatively closer to each other.

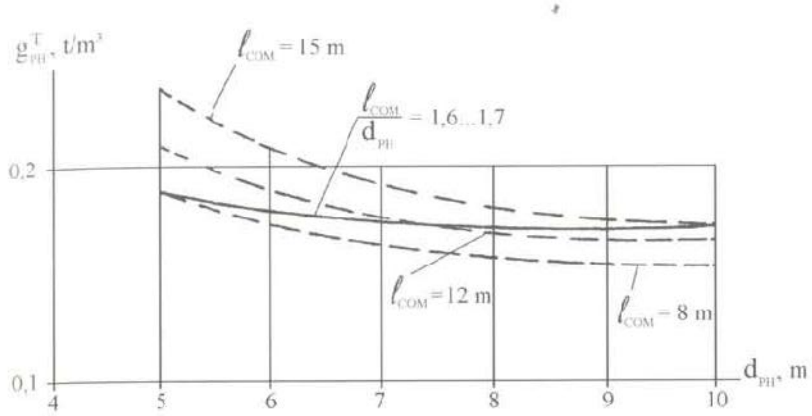


Fig. 3.3. The Pressure Hull Weight Index Versus the PH Diameter and the Compartment Length

In the second case the d_{PH} influence is much less than in the first case. Within the range of diameters and relative lengths of compartments $\frac{\ell_{COM}}{d_{PH}}$ =1.6 to 1.7 typical for modern submarines, it may be regarded as virtually non-existent.

Hence, at constant P_D and σ_T the PH diameter optimisation aiming at the absolute minimum of the PH weight at V_{PH} = const is meaningless. Transverse dimensions and the PH length-to-diameter ratio are in most cases dictated by the general arrangement of the submarine taking into account performance-wise requirements to the hullform, construction technology considerations and other factors but never by PH weight reduction considerations.

Let us now consider g^T_{PH} curves plotted as functions of H_{LIM} and σ_T for steel (Figs.3.4 and 3.5). Similar curves are routinely used in submarine design work.

Examining Figs.3.4 and 3.5 we may notice that at a constant design load (diving depth) the increase in σ_T results in a gradual reduction of the useful effect: benefits in terms of index values and PH weights drop and at higher σ_T values even tend to zero. In Fig.3.5 the line connecting points with conventionally extreme (for the effect upon the PH weight) values of σ_T is shaded.

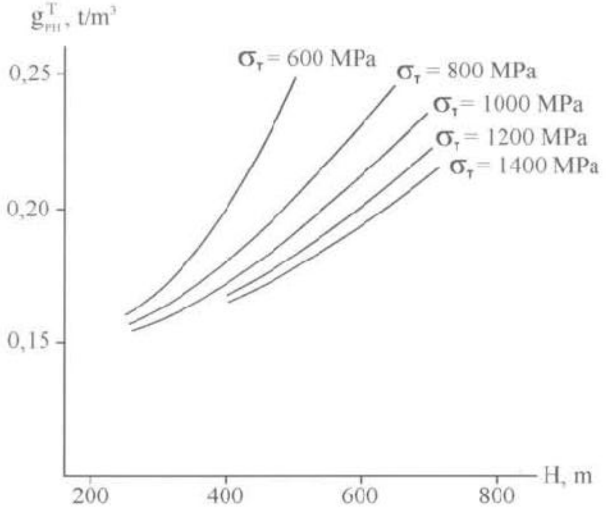


Fig. 3.4. The g^T_{PH} Index As a Function of the Diving Depth

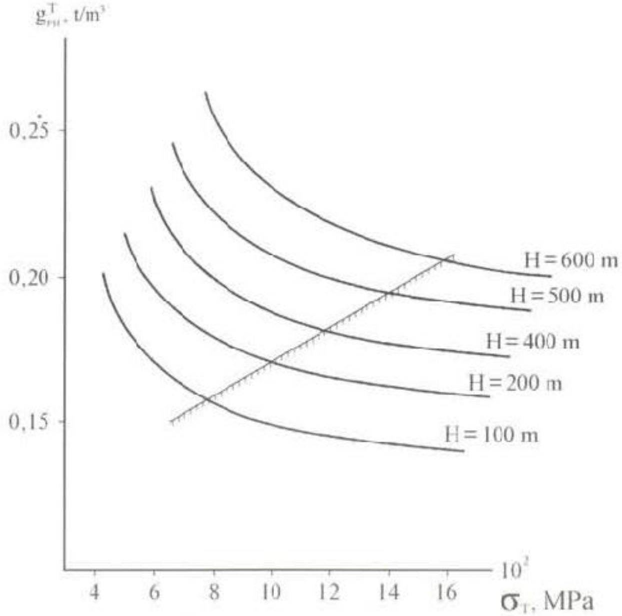


Fig. 3.5. The g^T_{PH} Index As a Function of the Material σ_T

The design load (diving depth) increase expands the domain of effective influence of the yield strength on the PH weight.

This pattern of σ_T effect upon the PH weight is explained by the buckling resistance factor because σ_T variations do not change the modulus of normal elasticity E, and therefore it is impossible to reduce plate thickness without changing the frame spacing length. Strains in the material will be below the allowable ones and its high mechanical properties will not be utilised to the full extent.

Strictly speaking, there is some reduction of the g^T_{PH} index with the increase in σ_T even when the plate thickness is determined by buckling resistance conditions, but this reduction is so small that it is irrelevant for our general conclusions.

Fig.3.6 gives an idea of the material type effect upon the PH weight index. We may see that new high-yield materials can considerably reduce the PH weight or, accordingly, increase the diving depth of the submarine.

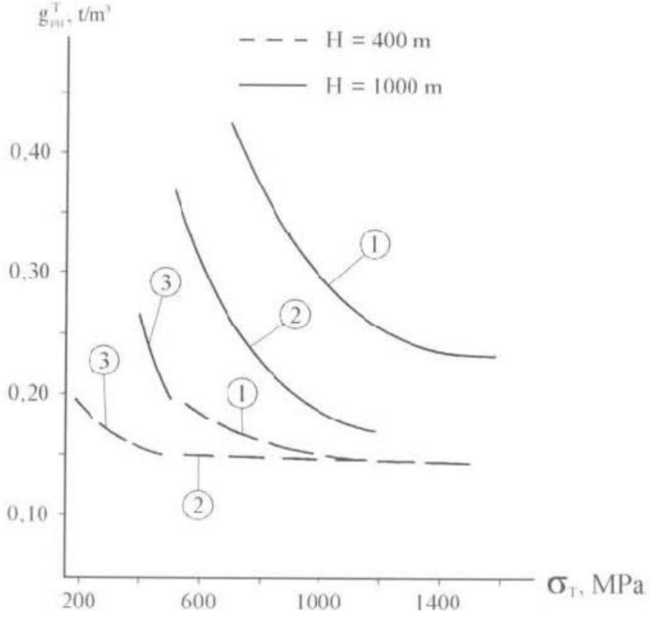


Fig. 3.6. Material Type Effect Upon
the Submarine Pressure Hull Weight Index
1 - steel, 2 - titanium, 3 - aluminium-magnesium alloy.

The PH weight also depends on the framing system. External frames increase the g^T_{PH} index compared to internal ones:

at $d_{PH} < 8.0$ m approximately by 1.5 to 3.0% at $d_{PH} \approx 8$ to 11 m approximately by 3.0 to 5.0%

Nevertheless, it should be kept in mind that when frames are mounted outside the PH they not only increase its weight but add extra buoyancy as well. Comparing the increase in the weight with the additional buoyancy, M.K.Glozman [1] has formulated a condition that, if satisfied, would balance (exactly or in excess) the increase in g^T_{PH} by the additional buoyancy.

$$r_{PH} \geq \frac{2\rho_{PH} - \rho}{\rho} y_0 \qquad (3.11)$$

where: r_{PH} – pressure hull radius;
y_0 – offset of the frame neutral axis from the pressure hull axis.

For steel hulls ($\rho_{PH} = 7.85$ t/m^3) the (3.11) condition is: $r_{PH} \geq 14.7\ y_0$.

In practical design the (3.11) condition as a rule is observed, though it should be noted that the choice between internal and external framing is actually more complicated as it is also necessary to consider general arrangement requirements, hull configuration (the double-hull system), service requirements, etc.

When PH dimensions are established, the g^T_{PH} index is a function of the frame spacing length ℓ, which can be selected in such a way that together with other structural elements of the PH – t, F – it would minimise the g^T_{PH} value.

However, this is a task of «internal» optimisation, it pertains to hull structure design and falls beyond the scope of present considerations.

Besides, the influence of the frame spacing on the PH weight is relatively minor and when choosing its length one should also consider its impact on labour requirements and, hence, duration and cost of the submarine construction [104].

Listed below are approximate methods for PH weight estimations that may be applied depending on the available initial information and on the problem to be solved. The PH volume is assumed to be known.

1. There is a close (in terms of the pressure hull) prototype.

a) material grades and design depths of the subject project and of the prototype are the same: $g^T_{PH} = g^T_{PH_0}$.

$$P_{PH} = P_{PH_0} \frac{V_{PH}}{V_{PH_0}} \qquad (3.12)$$

b) material grades and design depths of the subject project and of the prototype are different: functions $g^T_{PH}(P_D; \sigma_T)$ (see Fig.3.4), which act as extrapolators are used to scale the prototype g_{PH_0} to design P_D and σ_T and then to find the PH weight.

$$g^T_{PH} = g_{PH_0} \frac{g^T_{PH}(P_D; \sigma_T)}{g^T_{PH}(P_D; \sigma_{T_0})} \qquad (3.13)$$

$$P_{PH} = g_{PH} V_{PH}$$

2. There is no sufficiently close prototype.

The theoretical index $g^T_{PH}(P_D; \sigma_T)$ is found from Fig.3.4.

The PH weight is calculated with (3.5).

3. Configurations and dimensions of PH compartments are available.

Using an applicable standard procedure, they make tentative strength calculations for each PH compartment to find t_i and F_i (the frame spacing is assumed to be uniform along the entire hull). Then they apply the formula suggested by E.A.Gorigledzhan to determine the PH weight:

$$P_{PH} = (P'_{PL} \cdot k_{PL} + P'_{FR} \cdot k_{FR})k_{WD} + P_{SR} \qquad (3.14)$$

where: $P'_{PL} = \sum_1^n P'_{PL}$ – weight of the plating (ignoring cutouts and reinforcements) found as the total of compartment plating weights;
$P'_{FR} = \sum_1^n P''_{PL} - \Delta P_{FR}$ – weight of the framing by compartments less frame portions removed because of pressure tanks (Fig.3.7);
$\sum_1^n P''_{PL}$ – weight of the framing by compartments without the subtraction of portions removed not to cross pressure tanks;
ΔP_{FR} – weight of frame portions removed not to cross pressure tanks;
n – number of PH compartments;
$k_{PL} = 1.02$ – coefficient accounting for plating cutouts and reinforcement;
$k_{PL} = 1.03–1.05$ – coefficient accounting for framing reinforcement and stiffening, e.g., in way of removable plates

$k_{WD} = 1.02$ – coefficient accounting for the metal of welded joints;

P_{SR} – weight of large concentrated reinforcements (coamings of silos, etc.).

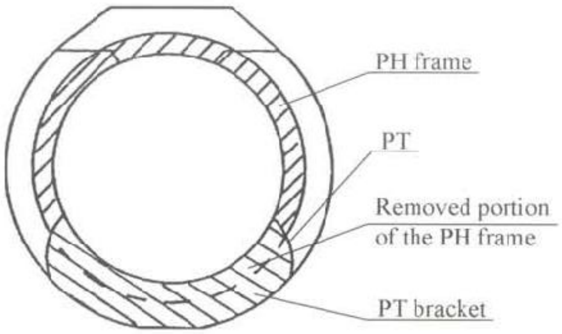


Fig. 3.7. The Pressure Hull Model for Weight Calculations with Formula (3.14)

There is a number of submarine hull structures that are calculated in the same way and for the same design load as the pressure hull. Their weights depend on same parameters as the PH weight.

These structures, collectively called «equistrong» (with the PH) include:

- end bulkheads of the pressure hull;
- pressure tanks;
- pressure superstructures.

For a tentative estimation of the total weight of these structures we can assume that:

$$P_{EST} = p_{EST} D_0 \tag{3.15}$$

Design load and material grade changes compared to the prototype are covered by re-calculating the p_{EST} index:

$$p_{EST} = \frac{P_D}{P_{D_0}} \cdot \frac{\sigma_{T_0}}{\sigma_T} \tag{3.16}$$

Formulae (3.15) and (3.16) do not reflect all factors that determine the weight of equistrong structures but their share in the load is not very considerable and this inaccuracy in their estimation does not result in any noticeable error in the submarine weight.

Index $p_{EST} = 0.03$ to 0.04 and with the increase of D_0 its value somewhat reduces.

The weight of end bulkheads has a steady share of about 0.01 of the displacement (0.03 to 0.04 of the PH weight). The major portion of the weight of all equistrong structures belongs to pressure tanks. The weight contribution of pressure superstructures on modern submarines is minor and never exceeds 0.2 to 0.3%.

When the designer already has compartment and tank schematics enabling him to establish characteristic dimensions of the PH, weight calculations for equistrong structures should be differentiated using either g_i indices or results of preliminary strength calculations for these structures.

End Bulkheads:

$$P_{ENB} = P^{F}_{ENP} + T^{AF}_{ENP} = g^{F}_{ENP} S_F + g^{AF}_{ENP} S_{AF} \tag{3.17}$$

where $S_{F(AF)} = \frac{\pi}{4}(d^{F(AF)}_{ENB})^2$ – cross-section area covered by the bulkhead.

Indices $g^{F(AF)}_{ENB}$ found from prototypes largely depend on bulkhead diameter (increasing with its growth) and structural configuration (plane or spherical bulkhead). In spite of the fact that the spherical bulkhead works in buckling resistance, its weight is 1.05 to 1.3 times less than that of the plane one.

Pressure Tanks:

$$P_{EGT} = \sum_{1}^{n} g_{EGT_i} V_{EGT_i} \tag{3.18}$$

It is also possible to use the 1st group index related to g_{EGT} as:

$$p_{EGT} = \frac{P_{EGT}}{D_0} = g_{EGT} \frac{1}{\rho} \left(\frac{\sum V_{EGT}}{V_0} \right) \tag{3.19}$$

where g_{EGT} – averaged weight index for equistrong tanks.

From (3.19) it follows that the share of pressure tanks in the submarine load balance is a function of the relative volume of these tanks. The weight of equistrong tanks always includes transverse bulkheads separating them from other tanks. The weight of bulkheads and pressure tank plating is comparatively high, and therefore, the g_{EGT} index is considerably larger than the PH index g_{PH} (sometimes 3 to 4 times higher). Due to these factors tanks with larger volumes have lower g_{EGT} indices.

The g_{EGT} index values are notably unsteady and can vary within 0.4 to 0.8 t/m³, the lower end of the range typically belonging to internal tanks.

The Light Hull

Following the design weight breakdown approach, the light hull (LH) in this case includes all structures left in Group 100 after we have separated the pressure hull and equistrong structures.

The LH share in the total load balance depends on the architecture of the submarine and on how extensive the outer hull (OH) is.

For double-hull submarines with large buoyancy reserves satisfying present requirements to surface trim floodability*, the LH weight is up to 45 to 50% of the weight of the entire hull (Group 100). The outer hull of such submarines contributes up to 60% of the LH weight.

The light hull includes structures of different types, different functions, different design loads and different materials. To calculate the weight of such a multipurpose system like the light hull in general (Fig.3.8), at the zero level of detail elaboration, we may use the correlation function (3.20) correcting it against the prototype.

$$P_{LH} = A_{LH}D_0^n + B_{LH} \qquad (3.20)$$

where B_{LH} is the weight of light hull structures that does not depend on the displacement.

The statistic data analysis has shown that quite satisfactory results could be obtained with the simplest formula for the light hull weight as a function of the normal displacement:

$$P_{LH} = p_{LH}D_0 \approx 0{,}16 \div 0{,}18D_0 \qquad (3.21)$$

Considering the huge share of the light hull in the submarine load balance, to obtain more accurate results its weight calculations should be elaborated in greater detail.

Let us consider the LH weight calculation at the first level of detail elaboration. Since at this level all components of the LH can be expressed approximately as functions of the displacement, Table 3.1 provides approximate values of $p_i = P_i / D_0$ indices.

---

*The submarine should remain afloat with one PH compartment and two adjacent main ballast tanks flooded [30], [89].

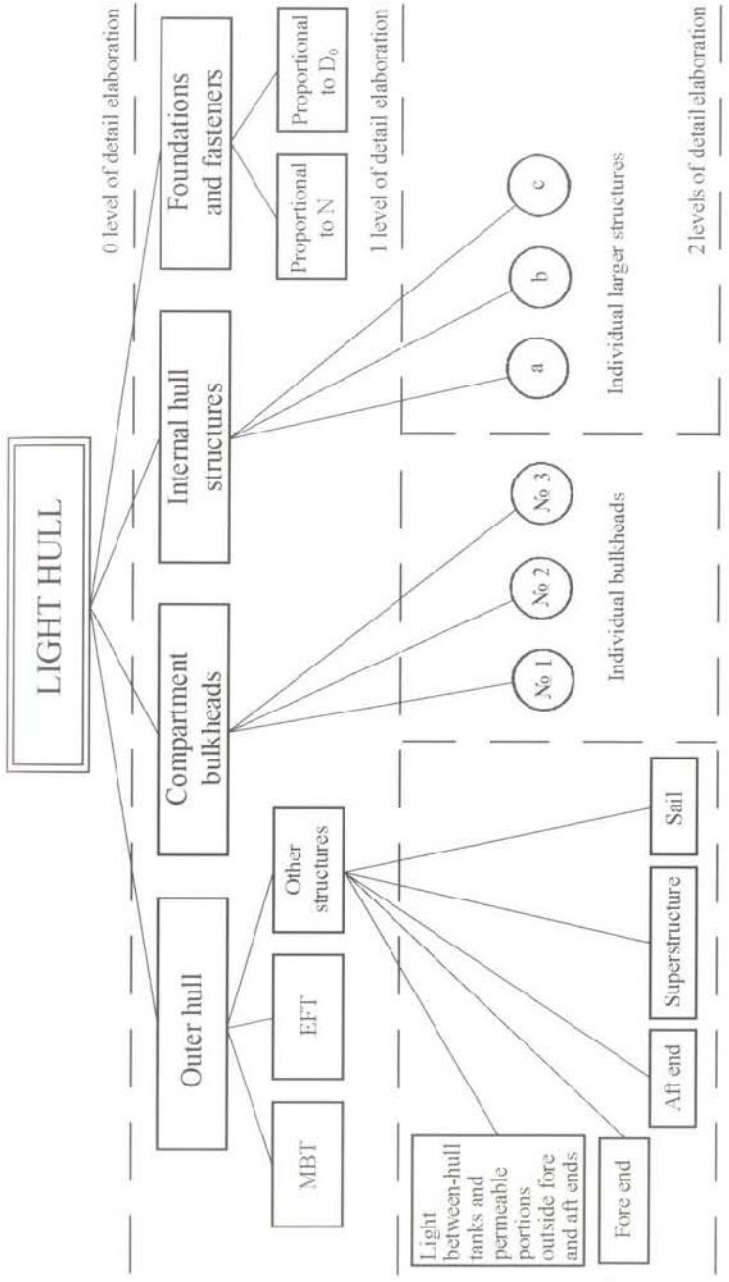


Fig.3.8. Light Hull Breakdowns for Different Levels of Detail Elaboration

Dimensions of the outer hull are the overall dimensions for the submarine, and therefore from the physical point of view it would be more appropriate to apply formulae containing the submerged displacement or the main dimensions. Nevertheless, formula $P_{OH} = p_{OH}D_0$ gives quite good results.

Table 3.1

Weight Indices of Light Hull Structures Referred to the Normal Displacement

Weight	Symbol	Index value
Outer hull	p_{OH}	0.10–0.11
Compartment bulkheads*	p_{CBHD}	0.020–0.025
Internal hull structures	p_{IHS}	0.02–0.03
Foundations and fasteners	p_{HF}	0.020–0.025
Total for the light hull	p_{LH}	0.16–0.115

* When a submarine is designed with an escape compartment, its restricting bulkheads are equistrong with the pressure hull. In this case their weight can be found from (3.17).

The weight of the outer hull can be refined if formulated as:

$$P_{OH} = P_{MBT} + P_{EFT} + P_{OTH}$$

where: P_{MBT} – weight of main ballast tanks;

P_{EFT} – weight of external fuel tanks;

P_{OTH} – weight of other parts of the OH, mainly permeable structures (permeable end structures, the superstructure, the sail, etc.).

On diesel-electric submarines, MBTs and external fuel tanks (EFT) occupy almost the entire between-hull volume and if there are end tanks, they partially take up end spaces as well. On nuclear submarines, due to the fact that the between-hull space is used for a large variety of purposes (biological shielding tanks, various special-purpose bays) the MBT share is less.

MBT and EFT weights can be expressed through some characteristics and particulars of the submarine. Let us formulate the weight of these tanks using indices of both the first and the second groups:

$$P_{MBT} = p_{MBT}D_0 \tag{3.22}$$

$$P_{MBT} = g_{MBT}V_{MBT}^{GR} \tag{3.23}$$

$$P_{EFT} = p_{EFT}D_0^{2/3} \tag{3.24}$$

$$P_{EFT} = g_{EFT}\,V_{EFT}^{GR} \tag{3.25}$$

where V_{MBT}^{GR} and V_{EFT}^{GR} – total gross volumes of tanks.

To consider net volumes we introduce coefficients k_{MBT} and k_{EFT} averaged for the subject groups of tanks and accounting for framing in tanks, PH plating, trapped water, etc. Besides, let us introduce another coefficient k_{NFC} to show what portion of the normal fuel capacity is allotted to the external tanks. Then

$$V_{MBT}^{GR} = k_{MBT}V_{MBT}^{NET} \tag{3.26}$$

$$V_{EFT}^{GR} = k_{EFT}\;k_{NFC}\;V_{EFT}^{NET} \tag{3.27}$$

From (3.22) and (3.23) we can, taking into account (3.26), derive formula for the MBT weight as a function of the displacement and of the relative reserve buoyancy (tentative):

$$P_{MBT} = p_{MBT}D_0 = g_{MBT}\frac{k_{MBT}}{\rho}\left(\frac{V_{MBT}^{NET}}{V_0}\right)D_0 = g_{MBT}\frac{k_{MBT}}{\rho}\varepsilon D_0 \tag{3.28}$$

where ε – relative reserve buoyancy.

From (3.24) and (3.25) with account for (3.27) we can derive the EFT weight formula:

$$P_{EFT} = g_{EFT}\cdot k_{NFC}\cdot k_{EFT}\frac{V_{EFT}^{NET}}{D_0^{2/3}} = g_{EFT}\frac{k_{NFC}\cdot k_{EFT}}{\rho_F}\cdot\frac{P_F}{D_0^{2/3}} \tag{3.29}$$

where P_F – full fuel capacity in tanks (useful capacity + trapped fuel in tanks).

From the general case of ship design it is known that:

$$P_F = g_F(1 + k_F)N\frac{R}{\vartheta_i} = g_F(1 + k_F)\frac{\vartheta_i^2}{C_i}\,R_iD_0^{2/3} \tag{3.30}$$

where g_F – specific fuel consumption;

ϑ_i and C_i – speed and Admiralty coefficient of the submarine speed condition for which they specify the sea range under diesel engines R (usually this is economic snorkel cruising);

$k_F \approx 0.02$ – coefficient accounting for trapped fuel left in tanks.

Substituting (3.29) and (3.30) into (3.24) we obtain an expression for the fuel tank weight.

$$P_{EFT} = g_{EFT} \frac{k_{NFC} k_{EFT} (1 + k_F)}{\rho_F C_{S\,NORT}} \vartheta^2_{SNORT} R_{SNORT} D_0^{2/3} \qquad (3.31)$$

Coefficients and indices for formulae (3.28) through (3.31) are established from prototypes. Some approximate values are:

$$g_{MBT} = 0.13\sim0.16\ t/m^3;$$

$$g_{MBT} = 0.20\sim0.22\ t/m^3;$$

$$k_{MBT} = 1.05\sim1.10;$$

$$k_{EFT} = 1.03\sim1.05.$$

Weights of other structures are found from:

$$P_{OTH} = P_{OTH} D_0 = (0.04 - 0.05) D_0 \qquad (3.32)$$

If all foundations are placed in the «Hull» group, their weight can be refined already at the first level of detail elaboration by formulating it as a sum of two components:

$$P_{HF} = p'_{HF} \sum_1^n N + p''_{HF} D_0 \qquad (3.33)$$

where $p'_{HF} \sum_1^n N$ – accounts for foundations of the power plant (PP) and the shaftline

$p''_{HF} D_0$ – accounts for foundations of general-purpose machinery and equipment together with fasteners.

At the second level of detail elaboration of the outer hull weight they calculate weights titled «other structures» (Fig.3.8).

Approximate formulae and indices for weights of outer hull structures may be found in Table 3.2.

Indices g_i and weights of bossings P_{BOS} are derived from prototypes with similar structures.

Table 3.2

Approximate Formulae for Weights of the Outer Hull Structures

Structures	Weight calculation formulae	Weight indices
Light between-hull structures (BHS)	$P_{BHS} = g_{BHS} V_{BHS}$, where g_{BHS} - averaged value for all light between-hull structures.	$g_{BHS} = 0.13\text{–}0.15\ t/m^3$
Fore end (FE)	$P_{FE} = g_{FE} V^{2/3}_{FE}$ or $P_{FE} = g'_{FE} S_{FE}$, where $V_{FE} = \delta_{FE} (lbh)_{FE}$ — gross volume; S — wetted surface of the end; $\delta_{FE} = 0.55\text{–}0.60$ for stem type; $\delta_{FE} = 0.70$ for body of revolution;	$g_{FE} = 1.15\text{–}1.40\ t/m^3$ $g'_{FE} = 0.22\text{–}0.28\ t/m^2$
Aft end (AFE)	$P_{AFE} = g_{AFE} V_{AFE} + g_{ST} S_{ST} + P_{BOS}$ or $P_{AFE} = g'_{AFE} S_{AFE} + g_{ST} S_{ST} + P_{BOS}$ $\delta_{AFE} = 0.5$ for AE of stabilising type; $\delta_{AFE} = 0.35$ for body of revolution;	$g'_{AFE} = 0.20\sim0.25\ t/m^2$ for stabilising type of AE; $g'_{AFE} = 0.25\sim0.30\ t/m^2$ for body of revolution
Superstructure	$P_{SST} = g_{SST} l_{SST} (b_{SST} + 2\ _{SST})$ or $P_{SST} = g'_{SST} S_{SST}$, where l_{SST}, b_{SST}, c_{SST} - superstructure dimensions	$g'_{SST} = 0.06\sim0.08\ t/m^2$
Sail	$P_{SAIL} = g_{SAIL} V^{2/3}_{SAIL}$ or $P_{SAIL} = g'_{SAIL} S_{SAIL}$ $\delta_{SAIL} = 0.60\text{–}0.70$ for foil-type sails; $\delta_{SAIL} = 0.57\sim0.59$ for larger-volume sails with vertical walls; $\delta_{SAIL} = 0.47\sim0.48$ for larger-volume sails with slant walls.	$g_{SAIL} = 0.90\sim1.10\ t/m^3$ $g'_{SAIL} = 0.13\sim0.15\ t/m^2$

If the aft end weight has to be found while control surface areas are not known yet, they can be estimated by re-calculations from the prototype proportionally to $V_{FS}^{2/3}$.

When stabiliser and plane/rudder areas are established, weights of these structures can be found with the help of indices from Table 3.3.

For formulae containing volumes of structures, the latter can be calculated with the help of the curve of frames or approximately estimated using block coefficients δ_i. Obviously, formulae involving structure surface areas S_i require more data.

Dimensions b and h of the end structures are dictated by the dimensions of the outer hull in way of PH end bulkheads while the length of end structures ℓ is counted from these planes.

Dimensions ℓ_{SAIL} and b_{SAIL} are measured conventionally at middle-height of the sail counting from the superstructure deck.

Table 3.3.

Weight Indices for Submarine Control Surfaces

Control surface	Index	Unit	Index values
Stabilisers	g'_{ST}	t/m^2	0.30 – 0.45
Vertical rudder with actuators	g'_{VR}	t/m^2	0.90 – 1.05
Fore hydroplanes with actuators	g'_{FPL}	t/m^2	1.50 – 1.60
Sail hydroplanes with actuators	g'_{SPL}	t/m^2	0.68 – 0.80
Aft hydroplanes with actuators	g'_{AFPL}	t/m^2	0.80 – 1.05

In underwater shipbuilding, follow-on modifications of a certain submarine type very often mean increasing the length of the PH and of the whole submarine. Transverse dimensions usually remain unchanged, mostly due to construction restrictions. In this case the weight of light between-hull structures and of the superstructure changes proportionally with the PH length. Provided their outfitting remains unchanged the weight of end structures can be approximately considered unchanged.

Updating estimation for compartment bulkheads weight at the second level of detail elaboration includes finding the weight of each bulkhead in accordance with its diameter, design pressure and structural type:

$$P_{BHD} = g_{BHD}(P'_D;\, d_{BHD})\,\frac{\pi}{4}\,d^2_{BHD} \qquad (3.34)$$

where d_{BHD} – bulkhead diameter.

The g_{BHD} index is derived from data on existing similar bulkheads of prototype submarines re-calculated to the subject design:

$$g_{BHD} = g_{BHD_0}\left(\frac{d_{BHD}}{d_{BHD_0}}\right)^{\ell}\frac{P'_F}{P'_{F_0}}\cdot\frac{\sigma_{T_0}}{\sigma_T} \qquad (3.35)$$

where $\ell = 1/2{\sim}2/3$ – power exponent accounting for the effect of the diameter;

P'_D and P'_{D_0} – design pressure for the bulkhead.

One may use results of systematic bulkhead strength calculations made varying d_{BHD} and P'_D, materials and other parameters like those shown in Fig.3.9 (for plane bulkheads).

The design weight of the bulkhead should include additions due to reinforcement and cutouts calculated from prototype data.

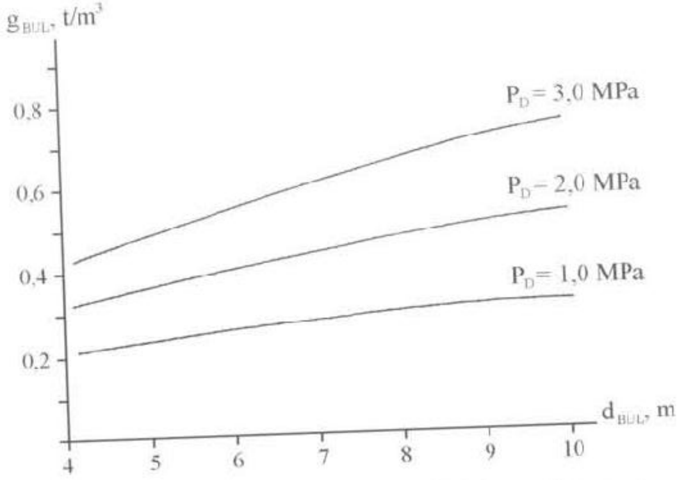


Fig. 3.9. Versus Design Load and Bulkhead Diameter

Weights of internal light structures can be refined by approximate estimation of the weight of larger internal tanks and decks based on their known volumes and areas. The weight of plating and stiffeners of light tanks inside the pressure hull may be estimated with g_{LT} = 0.18 to 0.19 t/m^3; the weight of decks is calculated with g'_{DEC} = 0.04 to 0.09 t/m^2.

3.2. Loads for «Hull Gears, Fittings» and «Hull Systems» Groups

The total weight of these load groups makes up approximately the same share of the normal displacement on different submarines of various designations.

$$P_{GS} = p_{GS}D_0 = (0.08 - 0.9)D_0 \qquad (3.36)$$

As may be seen in Fig. 3.10, the p_{GS} index only depends slightly on the displacement.

Since prototypes chosen as sources of data for weight indices do not differ much in terms of the displacement from what is expected in the new design, we may ignore the influence of the displacement upon P_{GS} and take this index from the prototype without any calculations.

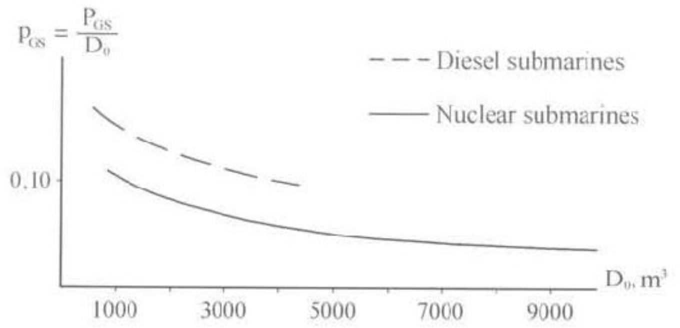


Fig. 3.10. The p_{GS} Index Versus D_0

Detail elaboration of loads due to gears and systems means finding individual weights of comparatively large gears and systems or groups of gears and systems with similar functions. Let us discuss some examples of such an elaboration.

Steering Gears (SG). For these devices it is advisable to apply scaling module $D_0^{2/3}\vartheta_{max}^2$, a value proportional to hydrodynamic forces on a plane/rudder, where ϑ_{max} is the full speed.

However, statistic data indicates that the most steady index is

$$P_{SG} = p_{SG}D_0 = (0.015 - 0.020)D_0 \tag{3.37}$$

Compressed Air and Gas System (AGS). Submarines actually have three such general-purpose systems: high pressure air (HPA), medium pressure air (MPA) and low pressure air (LPA) systems, as well as special-purpose compressed air systems for launching torpedoes and missiles. The weight of these systems may be regarded as proportional to the displacement:

$$P_{AGS} = p_{AGS}D_0 = (0.022 - 0.027)D_0 \tag{3.38}$$

The greater part of the AGS load is contributed by the high pressure air system. The basic purpose of the HPA system is to produce, store and deliver high pressure air for relevant consumers. To fulfil these functions, the HPA system has air bottles, compressors, air dryers, reducing and safety valves, filters, distributors and pipelines.

As long as the HPA storage capacity (Q_{HPA}) is known, we can easily derive an approximate formula for the AGS weight:

$$P_{HPA} = k_{HPA} \cdot P_{AB} = k_{HPA} \frac{Q_{HPA}}{V_{1AB}} (P_{1AB} + P_{1AIR}) \tag{3.39}$$

or

$$P_{AGS} = k_{AGS}k_{HPA} \frac{Q_{HPA}}{V_{1AB}} (P_{1AB} + P_{1AIR}) \tag{3.39a}$$

where k_{AGS} and k_{HPA} – coefficients for the weight of other system components;
P_{1AB} and V_{1AB} – weight of a standard air bottle and its payload volume;
P_{1AIR} – weight of the air in the bottle.

For the first approximation we assume that

$$Q_{HPA} = q_{HPA} D_0 \tag{3.40}$$

where q_{HPA} – a conventional standard for HPA storage capacity per ton of the displacement. Then substituting (3.40) to (3.39a) we obtain a formula that more accurately describes the relationship between P_{AGS} and D_0:

$$P_{AGS} = k_{AGS}k_{HPA} \frac{q_{HPA}}{V_{1AB}} (P_{1AB} + P_{1AIR})D_0 \tag{3.41}$$

Life Support Systems – these are ventilation, air regeneration, air conditioning, air purification systems, as well as sanitary and refrigeration systems that collectively hold about the same share as AGS:

$$P_{HS} = p_{HS}D_0 = (0.020 - 0.025)D_0 \tag{3.42}$$

Water Systems include, besides general-purpose ones, some weapon-support cooling and water systems. Altogether, their load accounts to about 1% of the displacement.

$$p_{WS} = (0.009 - 0.012)$$

The Diving and Surfacing System (DS) caters for the ultimate quality of the submarine: the ability to dive and surface. The system includes kingston valves and vent valves of MBT with their actuators and MBT LP blowing lines. The weight of this system depends on the number of MBTs (or indirectly on the reserve buoyancy) and on the number of tanks fitted with kingston valves. The latter factor has a significant impact, and therefore the weight index of the system is not very steady:

$$p_{DSS} = P_{DSS} / D_0 = 0.003 - 0.009$$

If the total number of MBTs and the contribution of tanks with kingston valves are known, we can approximately estimate the weight of this system as:

$$P_{DSS} = k_{DSS}\, n_{MBT} = (P_{1K} \cdot \overline{n}_K + P_{1VV}) \qquad (3.43)$$

where k_{DSS} – coefficient for other components included in the system;

$n_{MBT} = 2n^{side}_{MBT} + n^{end}_{MBT}$ – total number of MBTs on the submarine;

$\overline{n}_K = \dfrac{(n_{MBT})_K}{n_{MBT}}$ – relative amount of tanks fitted with kingston valves;

P_{1k} and P_{1VV} – weights of one kingston valve and one vent valve as taken from prototypes or earlier dedicated studies.

Usually they try to standardise these structures, at least within one submarine.

Hydraulic Systems. Due to everincreasing automation of control processes, hydraulic systems of modern submarines have become very extensive. Hydraulic actuators are used in control circuits of power plants, steering gears, diving and surfacing systems, for opening torpedo tube doors, caps of silos, etc. In the submarine load balance these systems take up approximately 0.4 to 0.6% of the displacement.

3.3. Loads for the «Mechanical Equipment, Pipelines and Systems of Power Plants»Group

The weight of the power plant (PP) is related to its power as

$$P_{PP} = p_{PP}\, N \qquad (3.44)$$

where p_{PP} – PP weight index (specific weight);
N – plant output, kW.

Fig.3.11 shows the trend of surface-to-submerged power ratio variation over the past 50 years [40], [50].

The specific weight depends on many factors including the power N, the growth of which results in the decrease in the specific weight of similar PPs. This is explained by the fact that any plant contains many components which show little response to changes in the power output [19], [73].

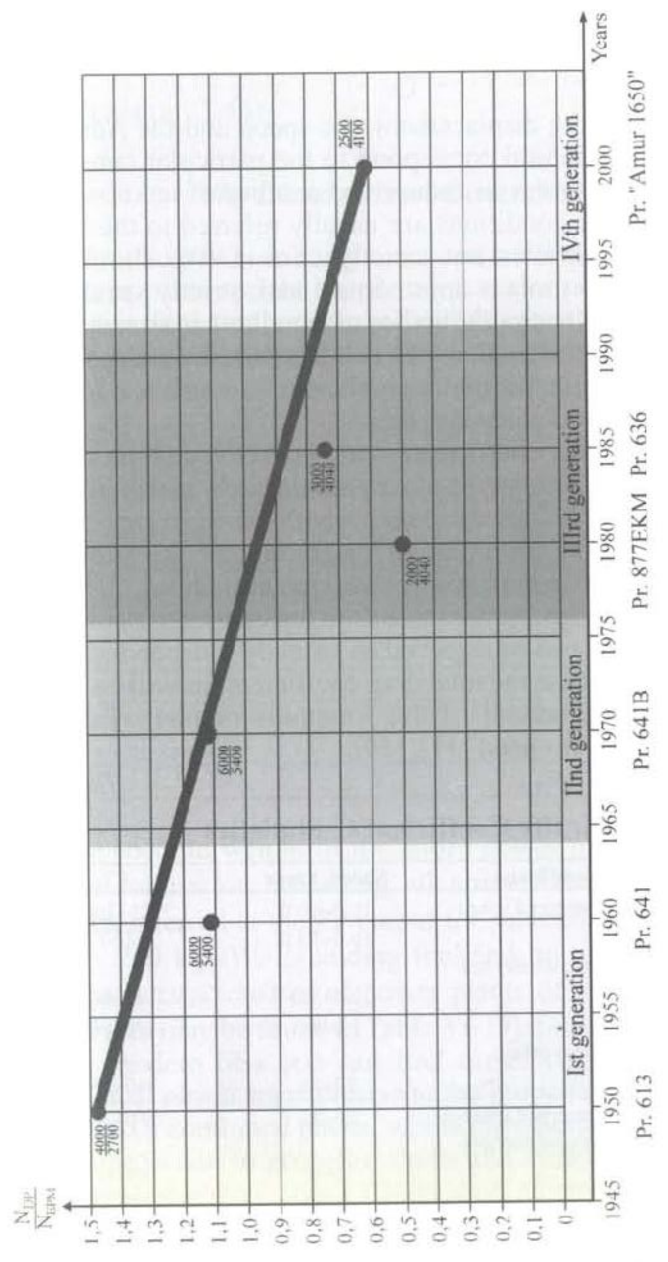


Fig.3.11. Variation Pattern of the Ratio Between Diesel Engine and Propulsion Motor Power Outputs for Diesel-Electric Submarines of Different Generations

Note. From the plot it is evident that diesel-generator capacity on Project 877EKM submarines was insufficient and that resulted in increasing the battery charging time and restricting submarine speed during charging. That design decision was forced by the lack of a diesel-generator of the required capacity. On Project 636, which is a follow-on of Project 877EKM they have installed a more powerful DG.

At early design stages the PP output is as a rule calculated from the formula of Admiralty coefficients

$$N_i = \frac{\vartheta_i^3 D_i^{2/3}}{C_i} \qquad (3.45)$$

Actual values of the displacement, the speed and the Admiralty coefficient in (3.45) should correspond to the particular considered service condition. In order to reduce the number of unknowns, all powers for all service conditions are usually referred to the normal displacement, though it is not exactly correct. We should also remember that this formula is approximate and, strictly speaking, it is true for geometrically similar bodies under all other assumptions.

At the same time the accuracy of power estimations depends on the correct choice of the Admiralty coefficient C_i which is a function of many parameters and characteristics.

Hence, the Admiralty coefficient should be selected very cautiously. Even when there is a prototype of very similar architecture, it should be scaled to the newly designed submarine with extreme care.

To give an idea of the order of magnitude of the submarine Admiralty coefficient under different service conditions, Table 3.4 demonstrates C_i statistics. At the same time for submerged sailing the Admiralty coefficient can be regarded as virtually independent of the speed because in this case the total drag coefficient (as will be shown later) is almost independent of the Reynolds number (Re) and, hence, of the submarine speed [31], [50].

Table 3.4

Admiralty Coefficient C_i Statistics

Hullform	Condition	Speed, knots	Ci
Stem type	Full submerged speed	12.0–16.0 16.0–19.0	85–100 150
	Economic submerged speed	2.0–3.0	40–60
	Snorkel	7.0–8.0	70–85
	Maximum surface speed	12–16	140–150
Body of revolution	Full submerged speed	16–21	250–360
	Economic submerged speed	3–4	40–60
	Snorkel	7–10	150–250
	Maximum surface speed	10–12	140–150

The Admiralty coefficient governs the power required for submarine propulsion. The power required to supply general-purpose onboard consumers is accounted for by introducing an absolute (in kW) or, as will be shown below, relative allowance to the power used for propulsion (3.45).

The Diesel (Diesel-Generator) Plant

When the power is known, we can make detailed calculations of the power plant weight based on its major components. Table 3.5 shows principal components and weights for a diesel-electric submarine PP in accordance with the design weight breakdown approach.

Table 3.5

PP Weight Breakdown for a Diesel-Electric Submarine

Description	Symbol	% of PP
Diesel engine plant	P_{DP}	14.3
Electric propulsion plant	P_{EPM}	8.2
Shafting	P_{SH}	4.5
Total main plants and shafting (Group 400)	$P_{DP} + P_{EPM} + P_{SH}$	27.0
Storage battery	P_{SB}	37.0
Fuel and oil (normal capacity)	P_{FO}	36.0
Total energy carriers	$P_{SB} + P_{FO}$	73.0
Total P	ΣD_i	100

The specific weight of the entire power plant of a large diesel-electric submarine, including all articles listed with normal fuel capacity, referred to the PP output for submerged propulsion (EPM) is $p_{PP} = 200$ kg/kW. Excluding fuel and oil, it is $p'_{PP} = 135$ kg/kW. Principal characteristics of power plants of Russian diesel-electric submarines may be found in Table 3.6 [3], [40], [41], [42], [44], [73].

On modern SSs one can find diesel engine plants (DP) with mechanical power transmission to the propeller shaft (directly or via a gear box), combined plants, which have both diesels with mechanical transmission to propeller shafts and auxiliary diesel-generators, and diesel-generator plants (DGP) with electric power transmission for exclusively electric propulsion (Fig.3.12).

Table 3.6

Principal Characteristics of Power Plants of Russian Diesel-Electric Submarines

Plant parameters	Ist generation			IInd generation	IIIrd generation			IVth generation «Amur 1650»
	613	611	641	641B	877EKM	636	636 *	
Type of diesel engines	37D	37D	37D	2D42	4-2DL42M	7-2D42	7-2D42	84 26/26
Number of diesels x power Speed, r.p.m.	2x2,000 h.p. 500	3x2,000 h.p. 500	3x2,000 h.p. 500	3x1,900 h.p. 500	2x1,000 kW 700	2x1,500 kW 750	2x1,750 kW 750	2x1,250 kW 1,000
Type of generators	–	–	–	–	PG-142	PG-167	PG167	SBDG-122-1000
Type of diesel-generators	–	–	–	–	DG-PT	30DG	3-DGM	28DG (AC)
Type of MPM	PG-101	PG-101 (on sides) PG-102 (middle)	PG-101 (on sides) PG-102 (middle)	PG-101 (on sides) PG-102 (middle)	PG-141	PG-165	PG-165	SED-1 («Permazin» type)
Number of MPMs x power Speed, r.p.m.	2x1,350 h.p. 420	2x1,350 h.p. 440 (on sides) 1x2,700 h.p. 540 (middle)	2x1,350 h.p. 440 (on sides) 1x2,700 h.p. 540 (middle)	2x1,350 h.p. 440 (on sides) 1x2,700 h.p. 540 (middle)	1x4,040 kW 500	1x4,040 kW 250	1x4,040 kW 250	1x4,100 kW 200
Type of economic speed PM	PG-103	PG-104	PG-104	PG-104	PG-140	PG-166	PG-166	SED-1 multi-speed
Number of economic speed PMs x power Speed, r.p.m.	2 x 50 h.p. 150	1 x140 h.p. 185	1 x140 h.p. 185	1 x140 h.p. 185	1 x139 kW 150	1 x95 kW 70	1 x95 kW 70	SED-1 multi-speed
Number of propeller shafts	2	3	3	3	1	1	1	1
Type of reserve propulsion motor	–	–	–	–	PG-168	PG-168	PG-168	submersible electric motor
Number of reserve PMs x power Speed, r.p.m.	–	–	–	–	2 x 75 kW 650	2 x 75 kW 650	2 x 75 kW 650	2 x 35 kW 500
Number of reserve propulsors	–	–	–	–	2	2	2	2
Type of SB	46SU	46SU	46SU	48SU	446	446	476	476
Number of SB groups x number of cells in a group	2 x 112	4 x 112	4 x 112	4 x112	2 x 120	2 x 120	2 x 120	2 x 126
Submerged range, miles speed, kts.	350 2	440 2	400 2	400 2	400 3	400 3	450 3	650 3
Snorkel range, miles speed, kts.	4,500 8	13,000 8	18,000 8	9,500 8	6,000 7	7,500 7	8,500 7	6,000 7
Surface range, miles speed, kts.	8,550 10	22,000 9	30,000 8	16,000 8	**	**	**	**

* Under study

** For SS of the IIIrd and IVth generations the surface range is not regulated.

A diesel (diesel-generator) plant should cater for the following service conditions:

- snorkel and surface propulsion at the specified speed;
- battery charging underway at snorkel and surface trims;
- MBT blowing with diesel exhaust gases when rising from the low-buoyancy trim;
- power supply to onboard consumers under all above-listed conditions.

Service conditions that dictate the required DP (DGP) power are economic speed in snorkel or surface trim with simultaneous battery charging (preferably by the 1st stage current).

In both cases onboard consumers should continue to receive their power supply.

The required DP (DGP) power for propulsion plus charging may be formulated as:

$$N = N_{PR} + N_{BCH} + N_{GPS} + N_{LOS} \qquad (3.46)$$

where: N_{PR} – power required for propulsion;
N_{BCH} – power required for SB charging;
N_{GPS} – power for onboard consumers;
N_{LOS} – power for losses in cables and cable runs (plant efficiency).

The power required for SB charging may be formulated as:

$$N_{BCH} = I_{BCH} U_{BCH} 10^{-3} n_{SB} \qquad (3.47)$$

where: U_{BCH} – voltage supplied during charging to one cell (U= 2.4 V for lead-acid cells and U = 2.05 V for silver-zinc cells);
I_{BCH} – charging current amperage;
n_{SB} – total number of cells (112 or more for lead-acid cells, 152 for silver-zinc cells).

At the initial stage of design work direct calculations of N_{GPS} and N_{LOS} are impossible because they require detailed design information. Therefore, let us describe N_{LOS} as a ratio:

$$\alpha_{LOS} = \frac{N_{LOS}}{\dfrac{N_{EPM}}{\eta_{EPM}} + N_{GPS}} \qquad (3.48)$$

where α_{LOS} – coefficient for losses in cables and cable runs;
N_{EPM} – power of electric propulsion motors;

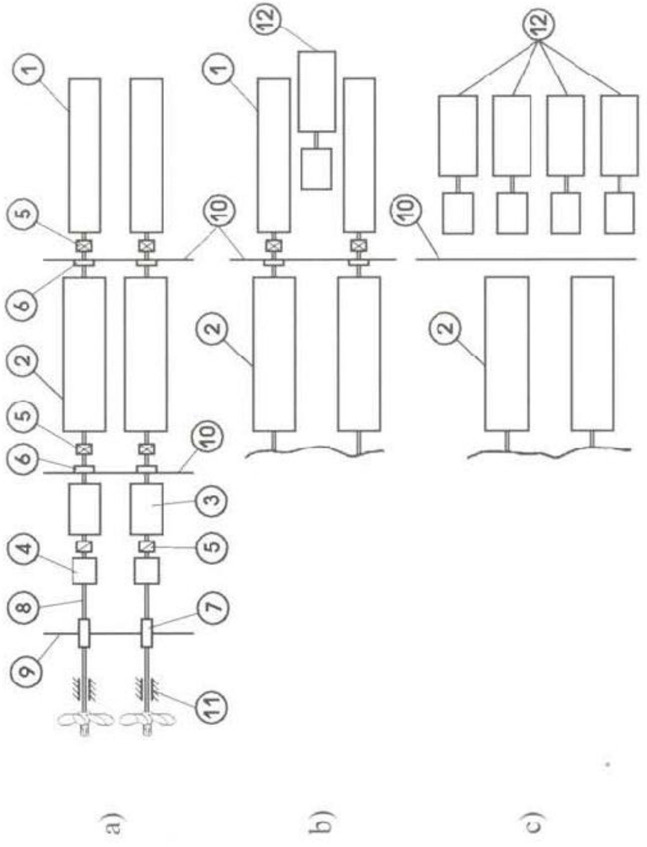


Fig.3.12. Diesel-Electric Submarine Power Plants

a) diesel-engine plant; b) combined plant; c) diesel-generator plant

1 - diesel engine, 2 - main propulsion motor, 3 - economic speed motor, 4 - thrust bearing; 5 - couplings, 6 - bulkhead glands, 7 - stern tube gland, 8 - shafting, 9 - pressure hull (or end bulkhead), 10 - compartment bulkheads, 11 - aft bossing, 12 - diesel-generator

η_{EPM} – efficiency of electric motors and assume that N_{GPS} for submarines of one type varies as:

$$N_{GPS} = a_{GPS} D_0^{2/3} = a_{GPS} \frac{1}{k_{FS}^{2/3}} D_{FS}^{2/3} \qquad (3.49)$$

where a_{GPS} – coefficient for the power required for general-purpose needs;
k_{FS} – coefficient relating the normal and the total submerged displacements.

Assuming that propulsion and charging tasks are distributed among individual motors in such a way that their power is utilised completely, we can obtain formulae for the total rated power of the DP (DGP) for the propulsion plus charging condition.

1. In snorkel (periscope) trim:

a) diesel plant, propulsion under diesel power:

$$N_{DE} = \alpha_{SNORT}\left[\frac{\vartheta^3_{SNORT}}{C_{SNORT}} + (J_3U_3 \cdot 10^{-3} n_{SB} + \frac{a_{GPS}}{\eta_{EPM} k_{FS}^{2/3}})(1+\alpha_{LOS})\right] D_{FS}^{2/3} = \beta_i D_{FS}^{2/3} \qquad (3.50)$$

b) diesel-generator plant, propulsion under economic speed electric power:

$$N_{DE} = \alpha_{SNORT}\left[\frac{\vartheta^3_{SNORT}}{C_{SNORT}\eta_{EMES}} + (J_3U_3 \cdot 10^{-3} n_{SB} + \frac{a_{GPS}}{k_{FS}^{2/3}})(1+\alpha_{LOS})\right] D_{FS}^{2/3} = \beta_i D_{FS}^{2/3} \qquad (3.51)$$

where N_{DG} – power output of the diesel-generator;
α_{SNORT} – numerical coefficient taken from the prototype;
β_i – coefficient relating the plant power with the displacement in formulae (3.50) through (3.52).

2. In surface trim:

diesel plant, propulsion under diesel power

$$N_{DE} = \frac{\vartheta^3_{SFB}}{C_{SFB}} D_{FSB}^{2/3} + (J_{BCH}U_{BCH} \cdot 10^{-3} n_{SB} D_{FS}^{2/3} + \frac{a_{GPS}}{\eta_{GEN}} D_{FS}^{2/3})(1+\alpha_{LOS}) =$$

$$= \left[\frac{\vartheta^3_{SFB}}{C_{SFB}}\left(\frac{k_{FSB}}{k_{FS}}\right)^{2/3} + (J_{BCH}U_{BCH} \cdot 10^{-3} n_{SB} + \frac{a_{GPS}}{\eta_{GEN} k_{FS}^{2/3}})(1+\alpha_{LOS})\right] D_{FS}^{2/3} = \beta_i D_{FS}^{2/3} \qquad (3.52)$$

In formulae (3.50) through (3.52) η_{GEN} – efficiency of propulsion motors in the generator mode.

It should be kept in mind that coefficients a_{GPS} and α_{LOS} for different conditions described by formulae (3.50) through (3.52) may be different.

The power required for charging batteries designed to ensure specified parameters of submerged propulsion, for general-purpose needs, as well as for losses in cables and cable runs, determines the power of diesel plant propulsion electric motors in the generator mode.

$$(N_{BCH} + N_{GPS})(1+\alpha_{LOS}) = (J_{BCH}U_{BCH} \cdot 10^{-3} n_{SB} + \frac{a_{GPS}}{\eta_{GEN} k_{FS}^{2/3}})(1+\alpha_{LOS}) D_{FS}^{2/3} \qquad (3.53)$$

This power should be matched with the motor mode power. It should be remembered that in the generator mode electric motors allow about 40% higher outputs than in the motor mode, i.e.

$$N_{GEN} \le 1.4 N_{MOT} \qquad (3.54)$$

If $N_{GEN} > 1.4N_{MOT}$, one should accordingly increase the motor mode power (to choose a motor with a higher output) or to install an auxiliary diesel-generator.

With the help of above-derived power expressions, we can obtain an approximate formula for PP (DG) weight estimation:

$$P_{DP(DGP)} = p_{DP(DGP)} N_{DE(DG)} = k_{DP(DGP)} \beta_i g_{DE(DG)} D_{FS}^{2/3} \qquad (3.55)$$

where $k_{DP(DGP)}$ – coefficient of the plant weight (for plants with diesel engines directly running the shaft $k_{DP(DGP)} = 1.8$ to 2.0);
$g_{DE(DG)}$ – mean specific weight of diesel engines (diesel-generators) proper in the assembled plant.

An Electric Propulsion Plant should cater for all submerged propulsion conditions and, if diesel engines are mechanically connected to shafting, and battery charging in the surface trim. In the latter case electric motors are fully or partially run in the generator mode. Where the submarine has fully electric propulsion, these tasks are covered by the diesel-generator.

Assuming that the electric propulsion motor power is dictated by the specified full submerged speed and using the general formula (3.44), we can derive a formula for approximate estimations of the electric propulsion plant weight:

$$P_{EPM} = p_{EPM} \Sigma N_{EM} = k_{EPM} g_{EM} \frac{\vartheta^3_{\downarrow max}}{C_{\downarrow max}} D_{FS}^{2/3} \qquad (3.56)$$

where g_{EPM} – mean specific weight of the propulsion motor proper, which depends on the type, speed and aggregate power of electric motors included in the plant;

$k_{EPM} = 1.25$ to 1.32 – coefficient for weight of the economic speed propulsion motors and auxiliary equipment of the plant (air coolers, propulsion motor fans, etc.).

The Weight of the Shafting is calculated from the power corresponding to the full submerged speed:

$$P_{SH} = p_{SH} N_{EPM} = p_{SH} \frac{\vartheta^3_{\downarrow max}}{C_{\downarrow max}} D_{FS}^{2/3} \qquad (3.57)$$

where $p_{SH} = 4.0$ to 4.5 kg/kW – specific weight of the shafting referred to the highest transmitted power.

If the speed of the propeller shaft and the shafting length are known, the weight can be calculated as:

$$P_{SH} = p_{SH_0} \left(\frac{N}{N_0}\right)^{2/3} \cdot \left(\frac{n_0}{n}\right)^{2/3} \cdot \left(\frac{\ell_{SH}}{\ell_{SH_0}}\right) \qquad (3.58)$$

where n_0; n – propeller shaft speed of the prototype and of the subject submarine;

ℓ_{SH_0}; ℓ_{SH} – respective lengths of propeller shafts.

The Storage Battery System (SBS) includes a storage battery (SB), wedging and connections of battery cells, loading and maintenance devices, mechanical systems for electrolyte agitation, ventilation and air conditioning in battery wells, storage battery water cooling.

For the first approximation to SB weight estimations the specific energy pick-up ΔW (kWh/t) is normally used, showing how many kilowatt-hours of electric power can be picked-up from one ton of the cell weight at the specified discharging rate. Fig. 3.13 shows the pattern of $\Delta W(t)$ curves for lead-acid (curve 1) and silver-zinc (curve 2) cells [24], [106].

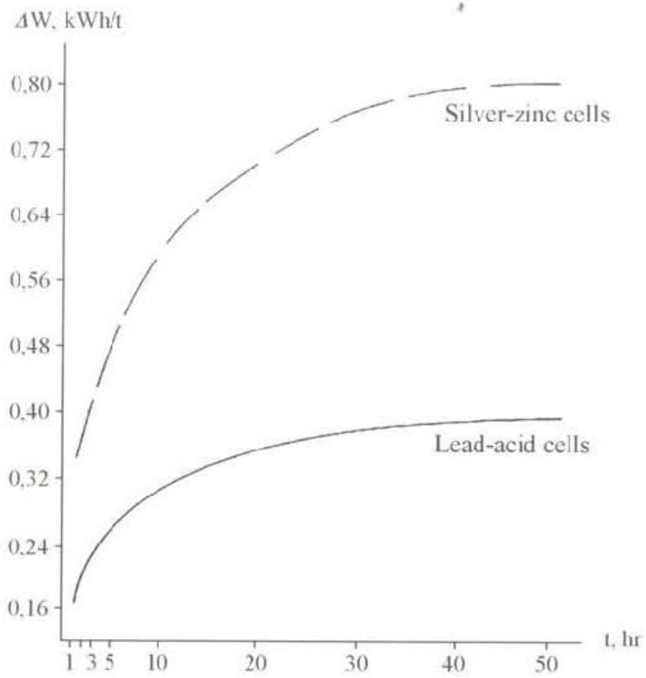


Fig. 3.13. Specific Power Pick-up As a Function of the Battery Discharge Time

If discharge parameters of the cell – current I(t) and mean voltage $U_{MEAN}(t)$ – are known, the specific energy pick-up is found as:

$$\Delta W(t) = \frac{J(t) \cdot U_{MEAN}(t) \cdot t \cdot 10^{-3}}{P_{CELL}} \qquad (3.59)$$

where t – discharge time, hr;

P_{CELL} – weight of one cell found from delivery specifications, t.

A general formula for the storage battery system weight can be written as:

$$P_{SB} = k_{SB} k_{DIST} P_{SB} = k_{SB} k_{DIST} \frac{W}{\Delta W} \qquad (3.60)$$

where: $k_{SB} = 1.15$ to 1.20 – coefficient accounting for the system weight;

$k_{DIST} = 1.02$ to 1.03 – coefficient accounting for the weight of the distillate for topping the cells.

For SSDEs, the storage battery is the only source of power when submerged (in this case air independent plants are not considered) that provides speeds and ranges specified in SDS, as well as power supply to all other consumers.

The general expression for the required SB power may be presented as:

$$W = (N_{PR} + N_{GPS} + N_{LOS})t \qquad (3.61)$$

where: $N_{PR} = \frac{N_{EPM}}{\eta_{EPM}}$ – SB power for propulsion;

N_{GPS} and N_{LOS} – power for general-purpose needs and losses found from (3.48) and (3.49);

$t = \frac{R_i}{\vartheta_i}$ – submerged time under subject service conditions.

Taking into account these functions and relationship (3.56), the required power expression becomes:

$$W = \left(\frac{\vartheta_i^3}{C_i \eta_{GEN}} + \frac{a_{GPS}}{k_{FS}^{2/3}}\right)(1+\alpha_{LOS})tD_{FS}^{2/3} \qquad (3.62)$$

Substituting (3.62) to (3.60) and taking into account that the SB should ensure the cruising range under all service conditions specified for the design (usually it is the full submerged speed for 1 hour and long-term economic speed cruising at 2 to 3 knots), we obtain the formula for the storage battery system weight.

$$P_{SB} = k_{SB}k_{DIST}(P_{SB})_{max} =$$

$$= k_{SB}k_{DIST}\left[\left(\frac{\vartheta_i^3}{C_i \eta_{GEN}} + \frac{a_{GPS_i}}{k_{FS}^{2/3}}\right)(1+\alpha_{LOS})\frac{t_i}{\Delta W_{t=t_i}}\right]_{max} D_{FS}^{2/3} \qquad (3.63)$$

where i is the designator of the subject service condition.

Having determined the SB weight for the specified service conditions, for subsequent calculations we take its maximum value. Value $\Delta W_{t=t_i}$ in formula (3.63) is found from delivery specifications for the cells planned for installation on the designed submarine.

The Weight of Fuel and Oil is calculated with the formula:

$$P_{FO} = g_F k_{OIL} k_F \frac{\vartheta^2_{SNORT}}{C_{SNORT}} R_{SNORT} D_{FS}^{2/3} \qquad (3.64)$$

where g_F = 0.20 to 0.22 kg/kWhr – specific fuel consumption in the snorkel mode;

k_{OIL} =1.04 to 1.07 – coefficient accounting for the fuel stock weight

k_F = 1.15 to 1.02 – coefficient accounting for the fuel left in tanks.

The Nuclear Power Plant

With a chosen type of the steam generating plant (SGP) and MPP configuration, the specific weight of the main power plant P_{MPP} depends on:

- main power plant output;
- MPP configuration, in particular, the plant formula (number of reactors – number of main geared turbines – number of propeller shafts);
- arrangement of the plant in the submarine hull;
- propeller shaft speed;
- composition of auxiliary equipment.

In submarine shipbuilding they use, as a rule, water-cooled and water-moderated SGPs. Therefore, the following description is applicable to this type of plant.

Fig.3.14 shows basic configuration of the main power plant of a nuclear submarine [10].

Weight ratios of nuclear power plant (NPP) components are given in Table 3.7 [10], [18], [26], [71].

Specific weights of MPP components in Table 3.7 refer to the shaft power.

The relationship between the NPP total weight and submarine displacement can be presented as:

$$P_{MPP} = p_{MPP}N = p_{MPP}\frac{\vartheta^3}{C}D_{FS}^{2/3} = k_{HF}k_{MPP}p_{MPP}\frac{\vartheta^3}{C}D_{FS}^{2/3} \qquad (3.65)$$

where values N, ϑ, C correspond to the full submerged speed.

Available information on weights and dimensions is very often limited to the MPP only and, as a rule, does not cover foundations and auxiliary components of the plant.

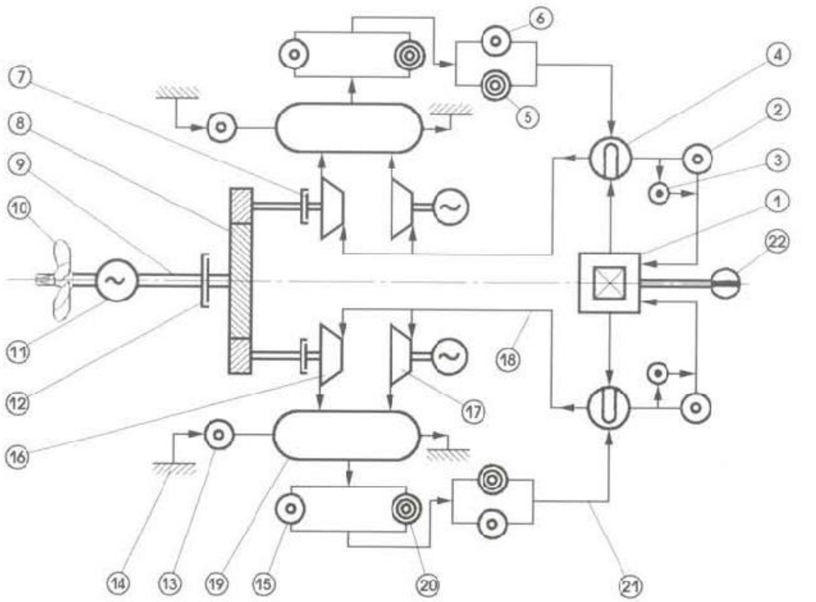


Fig. 3.14. Basic Configuration of a SSN PP

1 – nuclear reactor; 2 – main circulating pump of the 1st circuit; 3 – filter; 4 – steam generator; 5 – auxiliary feed pump; 6 – main feed pump; 7 – disengaging clutch; 8 – reduction gear; 9 – shaft line; 10 – propeller; 11 – propulsion electric motor; 12 – disengaging clutch of the propeller shaft; 13 – circulating pump of the main condenser; 14 – pressure hull; 15 – main condensate pump; 16 – main turbine; 17 – stand-alone turbo-alternator; 18 – main steam line; 19 – main condenser; 20 – auxiliary condensate pump; 21 – feed water pipeline; 22 – pressuriser.

Table 3.7

Nuclear Power Plant Weight Breakdown

Description	Specific weight, kg/kW	% of
Steam generating plant (SGP) without shield tank (SHT)	21.0 to 24.0	44.0 to 45.0
Steam turbine plant + turbo-alternator	11.0 to 10.0	22.0
Shield tank and steam-turbine plant foundations	6.0 to 7.0	13.0
Reserve propulsion motor	1.0	—
Shaft lines with propulsors	2.0	8.0
Diesel-generator plant	1.0	—
Total group 400	41.0 to 46.0	88.0
Storage battery system	4.5	9.0
Margins for power plant	1.5	3.0
NPP total	45.0 to 52.0	100

In formula (3.65) we introduce the following coefficients: $k_{HF} = 1.20$ taking into account the weight of foundations and $k_{MPP} = 1.20$ to 1.25 taking into account the weight of auxiliary components of the plant.

Fig. 3.15 shows the specific weight as a function of the power plant [10], [26], [71].

Weights of Auxiliary Components can be determined more accurately based on their own required power or energy values.

The Weight of Reserve Propulsion Motors (RPM) is found from the general formula (3.56):

$$P_{RPM} = p_{RPM} N_{RPM}$$

where p_{RPM} – specific weight referred to the power of the motor itself.

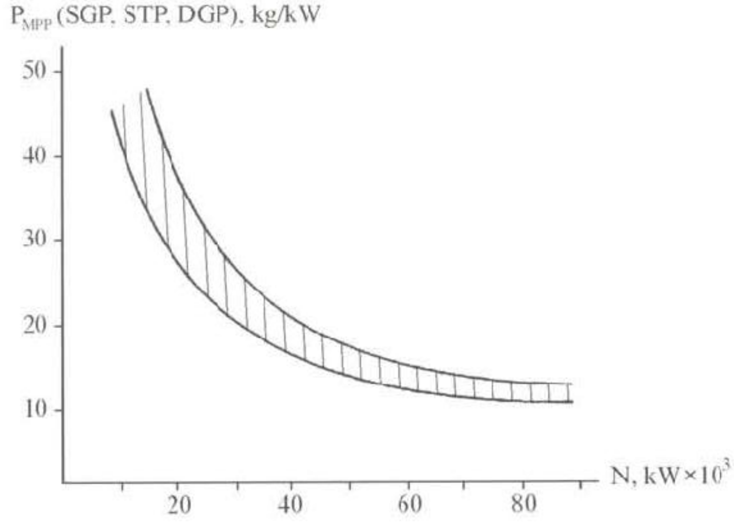


Fig.3.15. MPP Specific Weight to Power Ratio

The required SB capacity on a nuclear submarine is governed by the following requirements:

- SGP shut-down cooling in the case of shutdown at sea and subsequent restart;
- power supply to the minimum required number of general-purpose consumers during the interruption in SGP operation;
- propulsion at the minimum speed allowable due to submarine steerability considerations.

Taking into account the losses and assuming that the energy for the first of the above requirements depends on N while that for the second and the third requirements is a function of the displacement, we can write

$$W_{SB} \approx \lfloor (a'_{SB} N^{c}) t' + (a''_{SB} D_0^{2/3}) t'' \rfloor (1 + \alpha_{LOS}) \qquad (3.66)$$

where a'_{SB} and a''_{SB} – coefficients relating to the required SB capacity to the MPP power and the submarine displacement;

$t^{'('')}$ – anticipated duration of SB operation during reactor shutdown cooling, start and repair interval taking into account submarine propulsion and power supply to consumers.

The nuclear submarine storage battery should be configured of groups with a standard number of cells. The number of groups is dictated by the required SB capacity. In the view of survivability considerations, it is desirable to have at least two groups. When the SB required capacity is known, the weight of the storage battery system is found with formula (3.63), very approximately: $P_{SB} = (0.10 - 0.15)P_{MPP}$.

The Weight of Feed Water and Oil Stocks for the MPP should ensure one complete replacement for a single-shaft plant or for one independent propulsion group of a twin-shaft plant. If capacities and types of plants of the prototype and of the new submarine are very similar, the weight of these stocks can be taken from the prototype as an absolute value.

We should note that the obtained relationships $P_i(D_{FS})$ can be used for power plant weight estimations based on calculated displacement value only for very early approximations as they take into account just the larger components of the plant. The power plant weight determined in this way should be updated taking into account a more refined configuration of the plant (particular chosen motors, number of propeller shafts and power distribution between them, as well as the SB compiled of standard cell groups).

Air-Independent Propulsion Plants

And finally, let us consider one more type of power plant that is nowadays developed both in Russia and in many other countries: air-independent propulsion plants (operating without access to atmospheric air) for conventional submarines of displacements from 1,000

to 3,000 tons. It appears that at larger displacements the nuclear power plant is always more optimal. The idea of such an engine is not new. In Russia, in 1912, sub-lieutenant Nikolsky suggested a concept of a closed-cycle internal combustion engine operating with oxygen supply. The opportunity to implement this concept was made possible at the same time, at a test stand at the Baltiysky Shipyard. Practical work on a submarine with a single propulsion motor for both surface and submerged operation was placed on a broad footing in our country in 1930s under the leadership of S.A.Bazilevsky [38] and immediately after the Great Patriotic war a large series of Project 615 «QUEBEC» submarines (Fig. 3.16) were built.

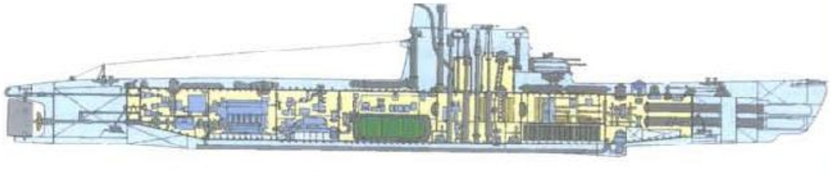
In 1943 German designers were working on the design of a submarine (XXVI series) equipped with a Walter turbine as a booster for submerged propulsion, and a similar plant was installed on Project 617 submarine in the USSR in 1951 (Fig.3.17).

Sea trials of the Project 613E «WHISKEY-AIP» submarine with fuel cells (Fig.3.18) were performed in 1988 [43], [46], [78].

The present boom in work on air-independent plants, which are used on submarines as auxiliary (additional) power plants, takes place at a qualitatively new level of science and engineering. There are evident successes in the creation of closed-cycle diesel engines (Russia, Germany, Holland, Great Britain, Italy), Stirling engines (Sweden), gas-dynamic turbines (France), and plants with fuel cells (Russia, Germany). Fig.3.19 schematically shows the fuel cell power plant compartment of a Russian submarine.

In a number of foreign publications [100] and national design studies [57], it has been shown that the arrangement of such auxiliary plants in separate compartments causes minor increases in the displacement and some reduction of the full submerged speed, but allows for several times greater submerged economic speed range in the search mode without using up the power of storage batteries (Fig.3.20).

At the same time, any engine type with all its advantages raises problems in submarine design and inevitably reveals some weak points. Therefore, new types of engines should be analysed in terms of major criteria for submarine power plants: specific power, explosion and fire safety, heat dissipation into the submarine environment, noise, operating costs, etc. Only after such an analysis can we make conclusions about the niche air-independent plants will find between classic diesel-electric and classic nuclear power plants, and on what kinds of submarines their installation is advisable.



Principal Tactical and Technical Characteristics

Submarine construction period, years	1953-1959
Number of constructed submarines, pcs	30
Normal displacement, m^3	405
Main dimensions, m: length beam	 56,8 4,5
Maximum diving depth, m	120
Power of diesel plant, h.p.	3 × 900
Full surface speed, knots	16
Full submerged speed, knots	15
Cruising range at full submerged speed, miles	56
Submerged range at economic speed, miles	360
Submerged endurance, days	4
Endurance, days	10
Liquid oxygen, tons	8,5
Chemical absorber, tons	15

Closed Cycle Plant

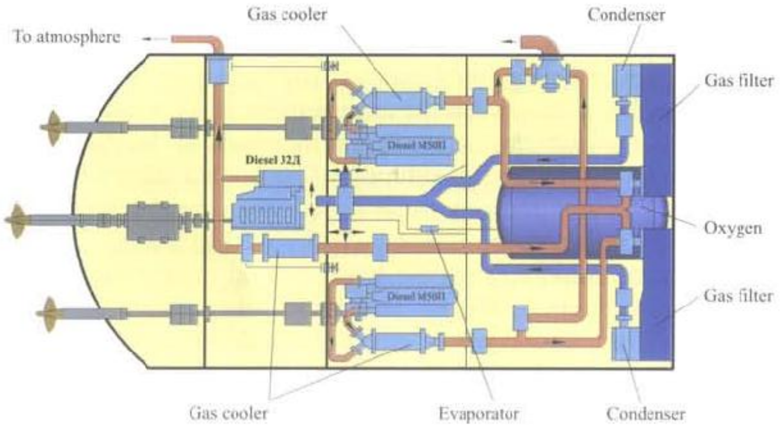
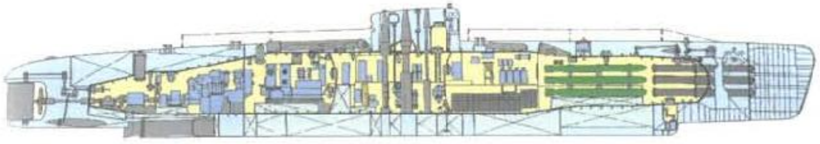


Fig.3.16. Project A615 «QUEBEC»
Submarine with a Single Motor for Surface and Submerged Propulsion



Principal Tactical and Technical Characteristics

Submarine construction period, years	1951-1952
Normal displacement, m^3	950
Main dimensions, m: length beam	 62,2 6,08
Maximum diving depth, m	200
Steam-gas turbine power, h.p.	7250
Full surface speed, knots	11
Full submerged speed, knots	20
Cruising range at full submerged speed, miles	120
Submerged range at economic speed, miles	132
Submerged endurance, days	8
Endurance, days	45
Hydrogen peroxide, tons	103,4
Light fuel, tons	13,9

Basic Configuration of a Steam-Gas Plant

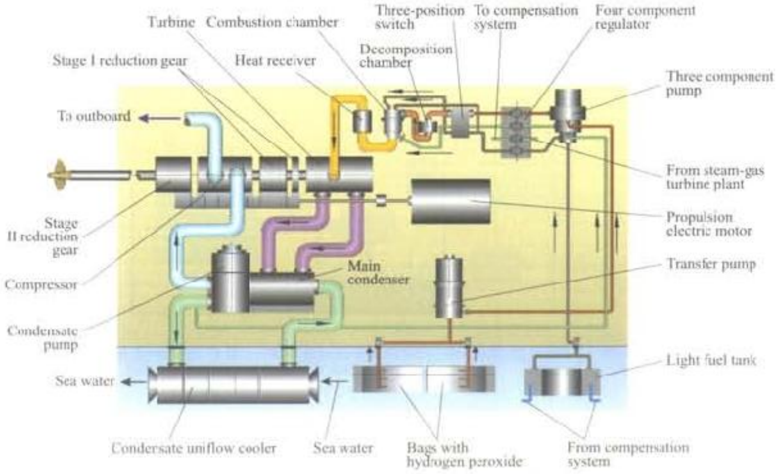
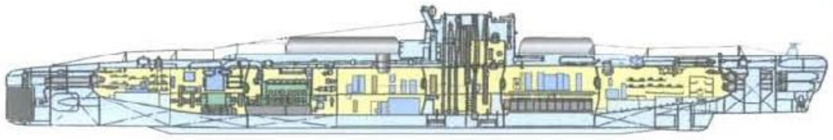


Fig.3.17. Project 617 «WHALE»
Submarine with a Steam-Gas Plant



Principal Tactical and Technical Characteristics

Period of sea trials, years	1988-1989
Normal displacement, m³	1265
Main dimensions, m: length beam	 76,0 7,3
Fuel cell power, kW	280
Full surface speed, knots	9
Full submerged speed, knots	5
Submerged range at economic speed, miles	1700
Endurance, days	30
Oxygen, tons	32
Hydrogen, tons	4

A Power Plant Based on Fuel Cells

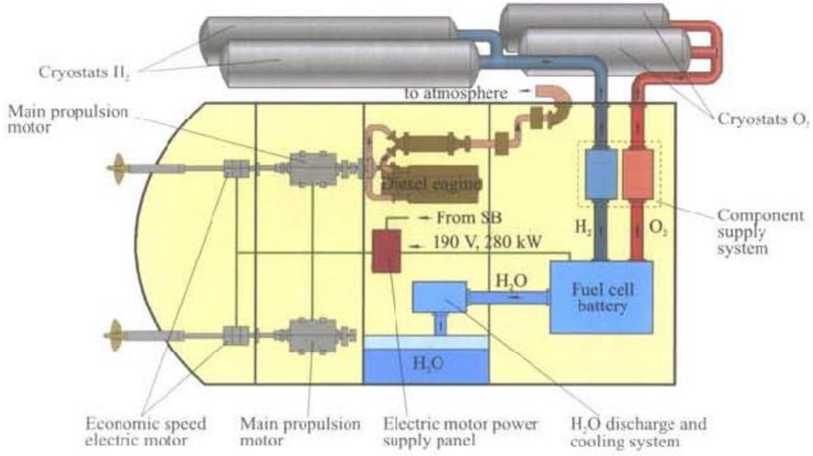


Fig.3.18. Project 613E «WHISKEY-AIP» Submarine with Fuel Cells

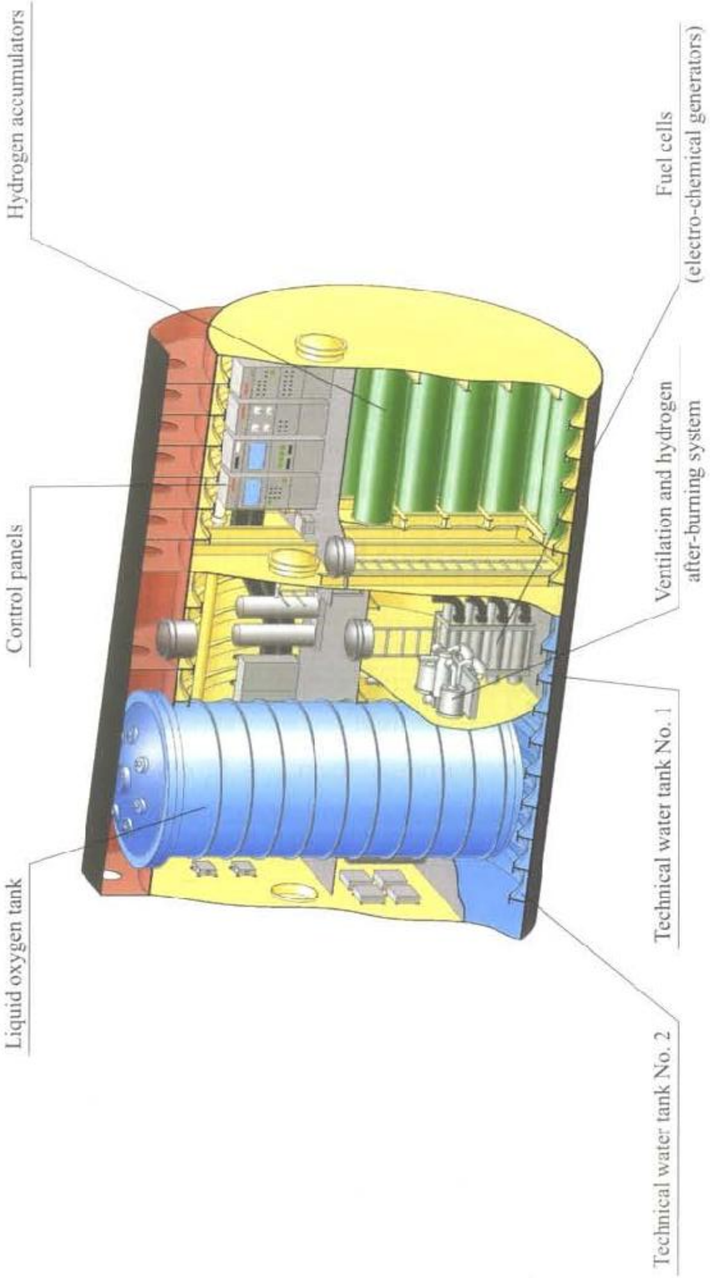


Fig.3.19. A Fuel Cell Power Plant Compartment

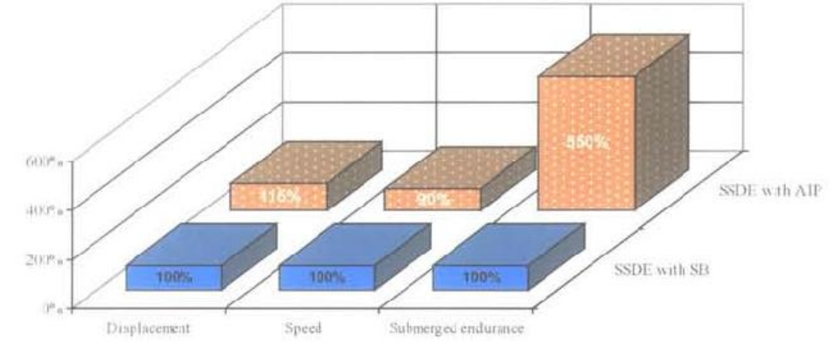


Fig.3.20. Results of an Analysis of Comparative Performances of Diesel-Electric Submarines with SBs and with AIPs.

3.4. Load for the «Electric Equipment, Cables of Electric Power Systems, Electric Networks and Radioelectronic Equipment» Group

Lists and designations of general-purpose electric equipment and cables are very diverse, and therefore it is rather difficult to obtain a physically justifiable and sufficiently complete formula for its weight.

Analysis of the submarine load balance shows that the weight index of electric equipment and cables $p_{EEG} = \frac{P_{EEG}}{D_0}$ is fairly steady for submarines of the same designation within one generation. Hence, at initial design stages this index can be derived from the prototype. Approximately it is $p_{EEG} = 0.04$ to 0.06.

The list of radioelectronic aids (REA), types of stations, and their main characteristics are indicated in the Submarine Design Specifications. The weight of equipment constituting radioelectronic aids is taken from delivery specifications or tentative data from the subcontractors-suppliers. In design studies one may use weights and dimensions of REA prototypes corrected for relevant design requirements and new technology developments.

The weight of REA does not depend on the design features of the submarine and therefore should belong to the group of independent («specified») weights. At the same time, the weight of outboard equipment, including antennas/arrays, depends on the diving depth (external

pressure on the equipment). This should be taken into account in calculations. The weight of cables for all purposes (trunk and local cables) is about 2 to 3% of the normal displacement of the submarine.

3.5. Load for the «Weapons and Their Supporting Systems» Group

For a submarine, this group includes weights of tools for engaging the adversary, as well as the weight of systems and units supporting their operation (fire control systems, etc.).

These weights are estimated based on the Submarine Design Specifications. Additionally, they also use data received from subcontractors and statistics from constructed submarines.

The weight of torpedo weapons can be estimated as:

$$P_{TS} = k_{TT} n_{TT} P_{TT} + (P_{WPT} + P_{SHUT} + P_{TOR}) n_{TT} + k_{RAC} n_{RELT} P_{TOR} + P_{TLG} \quad (3.67)$$

where $k_{TT} = 1.2$ to 1.3 – coefficient accounting for control devices;

n_{TT} – number of torpedo tubes (TT);

P_{TT} – weight of one assembled TT;

P_{TOR} – weight of one torpedo;

$P_{WPT} = 0.5$ to 1.2 t – weight of water in the round-torpedo annulus depending on the type of TT per one torpedo tube;

$P_{SHUT} = 0.3$ to 0.6 t – weight of the tube muzzle shutter;

$k_{RAC} = 1.4$ to 1.5 – coefficient accounting for the weight of storage racks;

n_{RELT} – number of reload torpedoes on the racks;

P_{TLG} – weight of the torpedo-loading gear.

Strictly speaking, this group can be considered as a constant weight that can be calculated with a high accuracy at the earliest stages of design work.

With a fixed calibre, the tube weight P_{TT} depends on the TT type (pneumatic, hydraulic, etc.), ejection depth, maximum diving depth of the submarine and TT material characteristics. At initial stages of the design, P_{TT} should be derived from the prototype. In case the maximum diving depth is changed, TT parts exposed to the full outboard pressure are re-calculated.

If the TT calibre is fixed, the weight of the shutter is determined by its length which depends on the outer hull shape in way of the torpedo exit point, as well as on the firing cone which is usually 1/18 [35].

Even with the same calibre, different types of torpedoes can be considerably different in weight (up to 1.5 times) [32], [52], [68]. This affects the weight of the water in the round-torpedo annulus. In conceptual design, when the weapon package is not yet specified in details, it is advisable to assume one type of torpedo for each calibre.

For approximate estimation of the missile weapon package weight one may use a formula similar to (3.67):

$$P_{MS} = n(P_{SILO} + P_{SIO} + k_{CAP}P_{CAP} + P_{MIS} + P_{WRT}) \qquad (3.68)$$

where n_{SILO} – number of silos for ballistic missiles or containers for cruise missiles;
P_{SILO} – weight of one silo/container;
P_{SIO} – weight of internal outfitting of one silo/container;
$k_{CAP} = 1.25$ to 1.30 – coefficient accounting for the weight of the silo fairing and cap actuator;
P_{CAP} – weight of one silo cap;
P_{MIS} – weight of one missile;
P_{WRT} – weight of the water in the round-missile annulus in one silo.

The silo body weight depends on its dimensions which are dictated by overall dimensions of the missile, by the maximum diving depth of the submarine and by characteristics of the material. When scaling P_{SILO} from a prototype, variations in these factors may be approximately accounted for with formulae for the PH weight. However, it should be kept in mind that g_{SILO} may be considerably larger:

$$P_{SILO} \approx P_{SILO_0} \frac{g^{T}_{SILO}(P_{MIS}, \sigma_T)}{g^{T}_{SILO_0}(P_{MIS_0}, \sigma_{T_0})} \cdot \frac{V_{SILO}}{V_{SILO_0}} \qquad (3.69)$$

where $g^{T}_{SILO} = \frac{P_{CYL}}{V_{CYL}}$ – weight index of the cylinder simulating the silo (similar to the g^{T}_{PH} index but including the bottom plate).

For scaling the cap weight we may use formula:

$$P_{CAP} = P_{CAP_0} \left(\frac{d_{SILO}}{d_{SILO_0}} \right)^{2.5} \left(\frac{P_{MIS}}{P_{MIS_0}} \right) \left(\frac{\sigma_{T_0}}{\sigma_T} \right) \qquad (3.70)$$

where d_{SILO_0} and d_{SILO} – diameters of the prototype submarine and the new submarine silos, respectively.

Other values in (3.68) are derived from delivery specifications for weapons, subcontractors' information and prototypes with similar weapons [34], [68].

3.6. Load for «Stocks and Complement», «Displacement Margin» and «Solid Ballast» Groups Stocks and Complement

Stocks and Complement

After the subtraction of stores for power plants, which has been done above, the index of the remaining part is $P_{SCR} = 0.02$ to 0.03, and the smaller value corresponds to submarines of greater displacements.

For a more accurate load estimation for the «Stocks and Complement» group, it is necessary to resolve a very important problem: to determine the number of crew members. On one hand, the submarine crew is required to maintain combat and general-purpose hardware but, on the other hand, personnel need food, water, air and berthing. If the number of personnel is too high, there are difficulties with accommodation spaces. For nuclear submarines of large displacements this issue is not very acute, but for diesel submarines with their limited displacements it becomes a problem and solving this problem is a crucial design task.

As a rule, the submarine complement can be approximately established at initial stages of the design. For this purpose they take Tables of Complement of the prototype submarine and make necessary corrections, including the account for two- or three-shift watch keeping, the assumed damage control and post-accident repair scenario, the extent of submarine control automation envisaged in the design.

When the number of personnel n_{ae} is established, we can calculate the weight of the crew and associated stores as:

$$P_{SCR} = p_{PER}n_{PER} + (P_{PROV} + P_{DRW})An_{PER} \qquad (3.71)$$

and regard the result as a constant (independent) weight. Here:
$p_{PER} = 100$ to 125 kg – weight of one man with personal belongings;
$P_{PROV} = 3.5$ kg – food allowance (including packing) per man per day;
$P_{DRW} = 6$ litres – fresh drinking water allowance (received at the base) per man per day;
A – endurance, days.

An additional amount of fresh water (in addition to 6.0 litres of drinking water) is provided by distilling plants.

In addition, these calculations should include an emergency subsistence of provisions and fresh water.

After we have calculated the weight of the complement and associated stocks, the share of trimming water, trapped water in tanks and air in the PH volume amounts to $p_{TTW} = P_{TTW} / D_0 = 0.005$ to 0.010.

The Displacement Margin

The displacement margin (DM) is divided into two parts: the design and construction margin, which is at the disposal of the design bureau and the shipyard, and the upgrading margin, which is at the disposal of the customer – the Navy.

The value of the design and construction margin depends on the design stage, the novelty of the project, and the availability of a close prototype. At the Technical Proposal development stage it can be $p'_{DM} = P_{DM} / D_0 = 0.030$ to 0.050, decreasing at the Detail Design phase to $p'_{DM} = 0.005$ to 0.010.

The unused portion of the DM is balanced by solid ballast.

The upgrading DM is specified in SDS and usually amounts to $p''_{DM} = 0.005$ to 0.020.

The issue of the advisable DM for future upgrading is rather complicated. From the military–and–economic analysis point of view, to restore submarine combat capabilities when military equipment (especially weapon and sensor packages) progresses very rapidly, it was reasonable, until recently, to keep a higher than above-indicated margin. However, since the mid 1980s, rapid advances in microelectronics and the introduction of integrated platform-sensor-weapon automatic control systems has resulted in drastic reductions of weights and dimensions of such equipment: by 1.5 to 2.0 times on submarines of the IVth generation. Therefore, this problem yet needs additional studies [93].

All types of displacement margins should be taken into account in the load balance table in such a way as to ensure the reserve stability. Usually, for submarines it is considered sufficient if the ordinate of the centre of gravity of the displacement margin is not lower than the total CG of groups «Gears» and «Systems», i.e. $Z_{DM} = Z_{GS}$. At early design stages this offset can be taken at the level of the pressure hull axis.

The abscissa of the displacement margin X_{DM} should be in the area of its anticipated utilisation or, when that is uncertain, at midsection.

The Solid Ballast

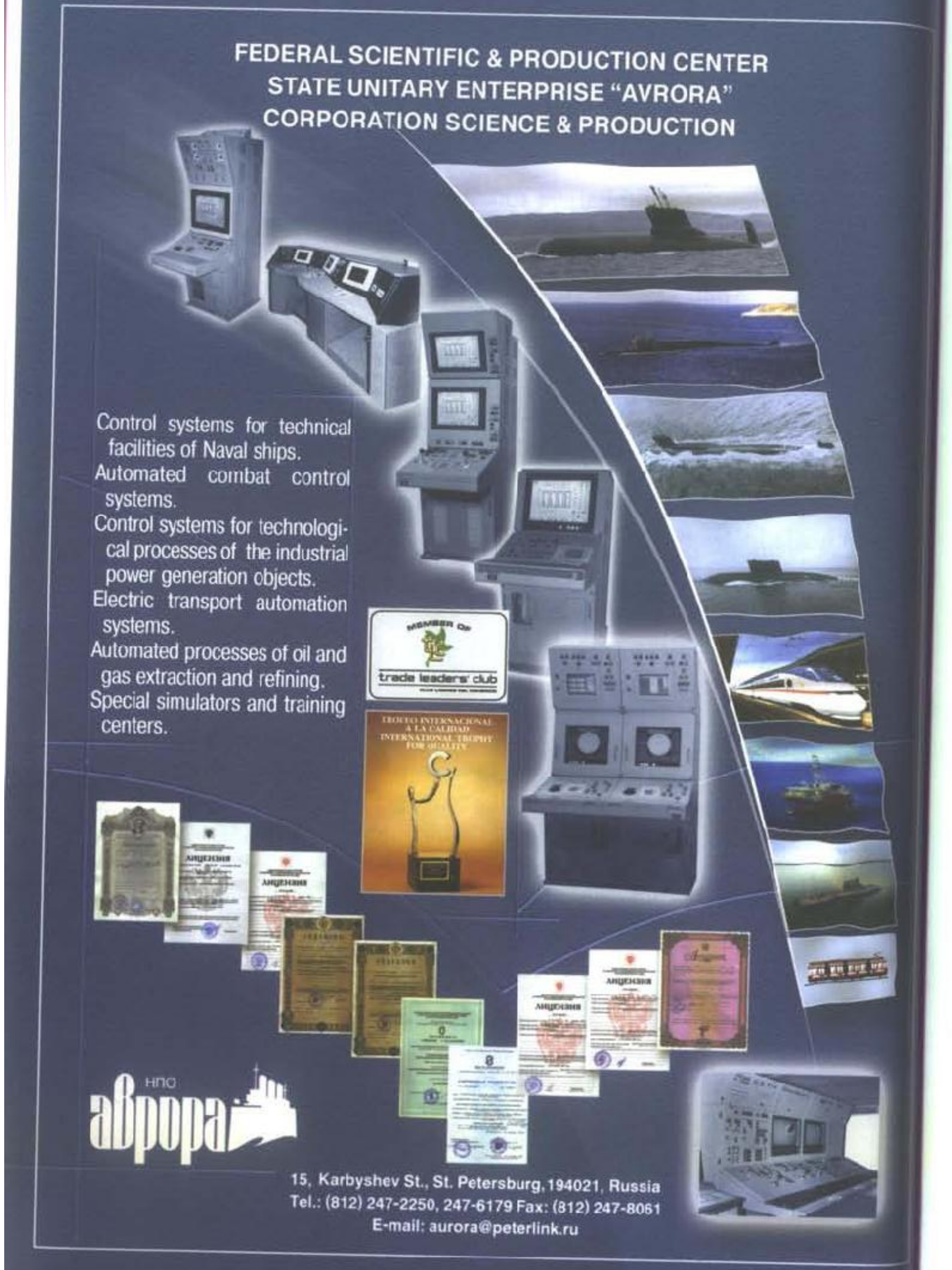
Solid ballast is an obligatory accessory of any submarine. It plays the role of a kind of governor necessary to achieve the vital equality $D_0 = \rho g V_0$, to trim the submerged submarine and to maintain required stability values.

The variety of solid ballast functions makes it difficult to offer a relationship for estimating its weight P_{BAL} based on any physical considerations.

When the particulars of a submarine are initially determined, it is conventionally assumed that $P_{BAL} = p_{BAL} D_0$. For most submarines of traditional types $p_{BAL} = 0.02$ to 0.04.

The required amount of the solid ballast and co-ordinates of its CG are more accurately determined after compiling the load balance and the constant buoyant volume tables.

The final amount of the solid ballast and the position of its CG are determined after the constructed submarine has been re-ballasted and heeled.



4. THE LOAD EQUATION AS A FUNCTION OF THE DISPLACEMENT. DETERMINATION OF THE DISPLACEMENT

4.1. Load Equation Derivation and Solution for the First Approximation

As stated in Chapter 2, the displacement, otherwise the weight of a buoyant body, D_0 is equal to the weight of water ρV displaced by this body. The displacement D_0 is a sum of weights of structures, machinery, equipment, weapons fuel, etc. constituting the submarine load balance, i.e.:

$$D_0 = \sum_{i=1}^{i=n} P_i \qquad (4.1)$$

Expression (4.1) is called the equation of load or the weight equation.

Some weights in formula (4.1) can be expressed as functions of the displacement $P(D_0)$. Other weights, let us designate them P_{IMD}, are specified and assumed to be independent of D. Therefore, we can write:

$$D_0 = P(D_0) + P_{IMD} \qquad (4.2)$$

The solution of the (4.2) equation gives the sought displacement corresponding to the specified independent weights P_{IMD}, as well as to parameters included in the $P(D_0)$ function, in particular, the sea range, relative weights, etc. Weights $P(D_0)$ can be calculated for any given D_0, but the sought displacement will correspond only to the solution of (4.2).

The graphic solution of this equation is shown on Fig.4.1. The solution of equation (4.2), i.e. $D_{0_{SOL}}$ is the intersection point of the weight curve $P(D_0) + P_{IMD}$ and the buoyancy straight line $D = D_0$. This is also the point where the law of Archimedes is satisfied. As we may see from Fig.4.1, the equation has the only solution.

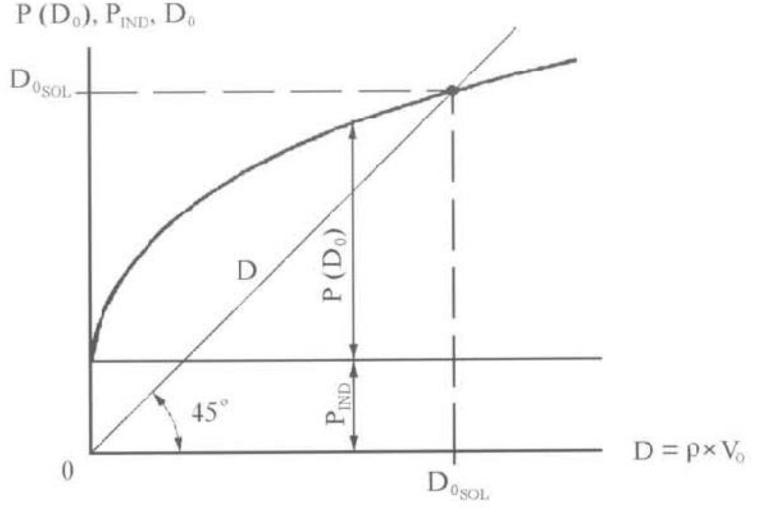


Fig. 4.1. Graphic Solution of the Equation of Load

It has been already mentioned in Chapter 3 that some weights depend on the displacement as a linear function while some are functions of $D_0^{2/3}$. Then, in a general form, function P(D) can be written as:

$$P(D_0) = AD_0 + ED_0^{2/3} \tag{4.3}$$

where coefficient A is the sum of relative weights directly proportional to D_0 while E is the sum of those depending on $D_0^{2/3}$.

The load equation corresponding to equation (4.2) is:

$$D_0 = AD_0 + ED_0^{2/3} + P_{IND} \tag{4.4}$$

Substituting $x = D_0^{1/3}$, formula (4.4) is reduced to a cubic equation and solved analytically [1].

Solving equation (4.4) by any method, we obtain the normal displacement in the first approximation.

4.2. Load Equation for the Second Approximation

Updating the displacement and the load balance of the designed submarine, as well as other design particulars, for the second approximation, is made by selecting the power plant configuration and updating other components of the normal displacement.

As nuclear submarines are usually designed for a given or assumed-in-advance power plant, the output and weight/dimension parameters of which are known, there is no need to select a plant. Let us consider setting up an equation in the second approximation for a SS, though it should be mentioned that the general approach to the equation of load is as true for SSNs.

The selection of the power plant components, i.e. motors, SB and other PP parts, should be preceded by the decision on the number of shafts and on the distribution of the total power among them. When this issue is settled taking into account all relevant factors, we can start the selection of actual motors from those available (by Manufacturer's catalogues) or under development.

Selection of Diesel Engines and Propulsion Motors

When selecting diesel engines for submarines, one should consider the following factors:

1) adequate power;
2) engine speed, especially if it drives the shaft line directly;
3) acceptable weight and dimensions allowing the arrangement of diesel engines in the submarine;
4) acoustic characteristics of the diesel engine;
5) ability of the chosen diesel engine to operate at increased counterpressures in the snorkel mode;
6) fuel consumption rate.

When selecting diesel engines by the required power N_i estimated from first–approximation data (see Chapter 3), it should be kept in mind that in real life the required power never coincides with the output of available engines. However, this is quite acceptable considering that any power requirement estimated with the formula of Admiralty coefficients is approximate. Thus, when diesel engines are selected and their weight is known, it is possible to find out the weight of the diesel plant:

$$P_{DP} = k_{DP}\sum_{1}^{n} P_{DE} \tag{4.5}$$

When selecting electric propulsion motors, the requirements are similar to that mentioned above about the selection of diesel engines. Additionally, it is necessary to take into account the fact that if the power plant of the submarine is not single-shaft, the power of electric motors obtained from first-approximation data has to be divided by shaft lines and this division may not always agree with the division of the diesel engine power. On the other hand, when diesel engines operate for the shaft directly, their revolutions should be matched in a certain way with the electric motor speed. Otherwise the propeller will be overloaded in one regime and underloaded in another. To match revolutions of the diesel engine and of the electric motor operating for the same propeller, it is necessary to have a power-propeller revolutions curve.

Thus, electric propulsion motors should be selected both by the power N_i and by the number of revolutions n. This condition makes the task more difficult and not always solvable. For completely electric propulsion designs this problem is non-existent, which was one of the major reasons for choosing electric-only propulsion plants for the IVth generation submarines.

When electric motors have been selected, similarly to the calculation of the diesel engine weight, we can estimate the weight of the propulsion plant with a formula like (4.5). $P_{EPM} = k_{EPM}\sum_{1}^{n} P_{EM}$

When the weights of above-discussed plants are established, they are transferred to the category of constant weights.

Selection of the Storage Battery System

With the help of the functions we have used when setting up the equation of load for the first approximation and of the obtained displacement D01 it is possible to calculate the weight of the storage battery system and the weight of the battery as such.

As already mentioned (see 3.3), the storage battery is made up of groups and the number of cells in a group is by no means arbitrary as it is determined by the required voltage delivered by the group and by the type of the storage battery.

The battery type is selected when the equation of load is set up for the first approximation because it largely dictates the value of the specific energy pickup ΔW and, hence, the battery weight (see Fig.3.13).

Thus, for the battery type established at the first approximation we have several alternative cells of different dimensions and weights P^{i}_{CELL}.

The required number of cells of weight P^{i}_{CELL} is determined as:

$$n^{1}_{CELL} = \frac{P_{SB}}{P^{1}_{CELL}} \qquad (4.6)$$

Knowing n^{1}_{CELL}, we find out whether it is possible to set groups with the given number of cells per group. After that we determine the number of groups and the number of cells n_{CELL}. In a general case n^{1}_{CELL} and n_{CELL} may differ one or other way. If this difference is not significant (let us assume it is within 5%), the storage battery is assembled of cells of weight P^{1}_{CELL}. If the difference is considerable, we repeat the procedure to find the number of cells of another type of weight P^{2}_{CELL} etc.

Having configured the storage battery, we can calculate the weight of the system and transfer it to the category of constant weights:

$$P_{SB} = k_{SB} \cdot k_{DIST} P^{i}_{CELL} n_{CELL} \qquad (4.7)$$

where k_{SB} – coefficient accounting for the weight of the system;
k_{DIST} – coefficient accounting for the weight of distillate for topping the cells.

In addition to the power plant components we can update some other weights included into the normal displacement of the submarine.

Based on updated results, the equation of load for the second approximation is set up as:

$$A'D_0 + E'D_0^{2/3} + P'_{IND} = D_0 \qquad (4.8)$$

Equation (4.8) will be considerably different from the equation of load for the first approximation (4.4).

Constant weights are now considerably larger as $P'_{IND} = P_{IND} + P_{DP}$ $P_{EMP} + P_{SB} + P_i$ and coefficient E' is smaller. Coefficient A' also may change.

Having obtained the displacement value from the second-approximation equation of load, we can compile the load balance table of the designed submarine for those major parts which were taken into account in setting up this equation. In this table it is helpful to enter data on submarine prototypes which have served as the basis for deriving respective weight indices and other parameters of the designed submarine.

Such a table enables us to check the correctness of the load equation solution and to compare the load balance of the subject project with those of other submarines. Deviations in values of weights per groups, particularly relative deviations (in percents of D_0), should be explainable from the point of view of Design Specifications.

4.3. Effects of Variations in Submarine Particulars and Independent Weights Upon the Load Balance. The Differential Form of the Load Equation As a Function of the Displacement. The Normand's Number

In various types of design estimations it is necessary to find out how the submarine displacement would change due to variations in different parameters (indices, tactical, technical or economical features) [6], [27]. In such tasks it may be convenient to use the differential form of the load equation describing the pattern of displacement variations due to small increments of relevant parameters:

$$\Delta D = \eta_{NOR}[\Delta P(D_0) + \Delta P_{IND}] \tag{4.9}$$

Coefficient η_{NOR} is called the displacement variation factor or the Normand's number. From (4.9) it follows that

$$\eta_{NOR} = \frac{\Delta D}{\Delta P(D_0) + \Delta P_{IND}} \tag{4.10}$$

i.e. the Normand's number is the ratio of the displacement variation due to a change in submarine parameters and independent weights. The limits of formula (4.9) applicability have not yet been studied adequately but for practical purposes we may expect rather accurate results at weight variations within 20% of D_0.

To calculate the variation of displacement ΔD by formula (4.9), it is necessary to find out both η_{NOR} and the weight variation $\Delta P(D_0)$ due to changes in submarine parameters assuming the displacement remains unchanged.

The variation of independent weights is calculated quite easily:

$$\Delta P_{IND} = P_{IND_1} - P_{IND_0} \tag{4.11}$$

Variations of weights which depend on the displacement and a number of submarine parameters can be found by finite difference calculations. E.g., when it becomes $P_{PH} = P_{PH_1}$ the PH load changes as:

$$\Delta P_{PH} = P_{PH_1} - P_{EST_0} = (p_{PH_1} - p_{EST_0})D_0 \neq \Delta p_{PH} D_0 \tag{4.12}$$

Similarly, it is possible to formulate load variations for all other groups. The result is:

$$\Delta P(D_0) = \sum_1^n \Delta P_i \tag{4.13}$$

The simplest expression for the Normand's number is written when the subject change $P(D_0) + P_{IND}$ occurs only due to the change in P_{IND}, i.e. $\Delta P(D_0) = 0$, and $\Delta P_{IND} \neq 0$.

$$\eta_{NOR} = \frac{1}{1 - \frac{dP_0(D_0)}{dD}} = \frac{1}{1 - A^{2/3}E \frac{D_0^{2/3}}{D}} \tag{4.14}$$

where $\frac{dP_0(D_0)}{dD} = \frac{P_{PH_0}}{D_0} + \frac{P_{LH_0}}{D_0} + \frac{P_{GS_0}}{D_0} + \ldots + \frac{2}{3}\left(\frac{P_{PH_0} + P_F + P_{SB}}{D_0}\right)$

With these formulae we can calculate η_{NOR}, e.g., when there is a change in weapon or ammunition weights. Quite often formula (4.13) is used even for $\Delta P(D_0) \neq 0$ (the very condition it was originally derived for by Jacques-Augustin Normand). The accuracy of calculations is slightly reduced, but at the same time calculations are simplified and, besides, it becomes possible to use one constant η_{NOR} for several options of parameter and independent weight variations.

Using relationship (4.13) it is possible to formulate displacement variation for A (when, e.g., the diving depth is changed and, accordingly, the weight of pressure structures becomes different):

$$\Delta D = \Delta A D_0 \eta_{NOR} \tag{4.15}$$

displacement variation for E (when PP power, speed and, accordingly, the weight are changed):

$$\Delta D = \Delta E D_0 \eta_{NOR} \tag{4.16}$$

displacement variations for ê, i.e. when the constant weights are changed (weapons, sensors):

$$\Delta D = \Delta P \eta_{NOR} \tag{4.17}$$

The value of the Normand's number for submarines is within $\eta_{NOR} = 3$ to 4 and it shows by how much the displacement can increase when the load grows. E.g., when the load increases by 100 t, the displacement increases by 300 to 400 t. The reason for this growth is a large contribution of displacement-dependent weights.

As follows from the above-said, the application of the differential form of the load equation is very closely related to the weight breakdown approach. The latter is governed by the considered task and, depending on the aim of the study, the composition of weight groups may change.

It should be mentioned that the larger the number of submarine equipment weight classed as constant weights, the more reliable the result obtained with the load equation and the Normand's number, and the less the value of this number.

Thus, the process of submarine load balance calculations at different design stages can be presented as a continuous growth of the constant weight share. At the Detail Design stage, when all weights are determined rather accurately and the load balance can be changed only at the expense of the displacement margin, the displacement increment becomes zero.

4.4. Load Control

By «load control» we understand a set of administrative and technical measures directed toward ensuring that the boat can be trimmed at all stages of her design, construction, trials and service.

The essence of submarine load control efforts boils down to the following procedures:

- prediction of the submarine load balance variations at all stages of design, construction, trials and service life;
- load control for equipment installed in the submarine according to the design documents issued in the process of design;
- displacement margin management;
- formulation and enforcement of load limits;
- weight control during construction (control by weighing);
- reballasting and heeling the submarine upon the completion of construction;
- load control for equipment installed for the period of submarine sea trials;
- load control for equipment installed during submarine upgrading;

Prediction of Submarine Load Balance Variations. The prediction of changes in the submarine load balance starts at the very early stages of the submarine design. Submarine load calculations made based on design formulae and statistic indices serve as initial information for work at subsequent design stages.

Having such a calculation available, the designer applies the method of expert evaluations to determine the most probable directions of submarine load balance changes based on information about innovations made in submarine design. Predictions, made jointly by specialists of the design bureau and companies developing the equipment, of possible changes in loads of individual types of submarine equipment serve as a basis for making decisions on assigning the value of the displacement margin for later design stages. In addition to the prediction of changes in the submarine equipment weight, they also make a prediction of the centre of gravity position for this additional weight.

Simultaneously with the prediction of the design-associated submarine load variations, a similar prediction is made for submarine load changes during construction. The results of this prediction are used for selecting the value of the construction displacement margin. As a rule, this value depends on the experience and equipment (machinery and appliances) of the shipyard selected for the submarine construction, as well as on non-traditional technologies required for the subject submarine (when the shipyard has to introduce the block and module method or different construction materials, e.g., when the chosen main structural material is a high-tensile steel which is better for strength but more labour consuming in terms of welding).

In parallel with the above-described work, they evaluate prospects of upgrading the boat within her life cycle and consider how such modifications may affect the submarine load balance.

All components of the displacement margin (for design, construction and upgrading of the submarine) are closely related to each other. Thus, if the displacement margin is not fully expended for design purposes by the completion of the Detail Design documents (the Detail Design stage), the remaining portion is usually included into the upgrading displacement margin. Similarly, the upgrading displacement margin increases if the construction displacement margin is not spent completely. However, in case of an unexpected increase in the submarine load at any design stage the «overweight» can be cleared at the expense of reducing the construction displacement margin. Then they have to apply more «stringent» load control measures during construction and to reconcile some design decisions.

Load Control by Detail Design Documents (drawings, diagrams, and lists in accordance with which the submarine is constructed) aims to obtain complete and reliable information about the submarine load balance. The load control is a component of the general Quality Assurance philosophy for documents issued by the design bureau. It is guaranteed by a system under which all generated documents must be approved by the Load Department. Such a form of control enables any design documents with incomplete or unreliable information in terms of the load balance to be spotted in time.

In the process of load control by the Detail Design documents they check all documents for the following information:

1) number of the Detail Design document;
2) description of equipment installed in the submarine according to this document;
3) subject equipment station (numbers of frames between which it is installed);
4) weight in tons (with the accuracy of up to 0.001 t);
5) coordinates of the centre of gravity in the submarine reference grid (from the midship station – X, from the base plane – Z, from the centre line – Y) – with the accuracy of up to 0.01 m;
6) moments of weights (with the accuracy of up to 0.01 tm);

If the design document is developed for the installation of some equipment containing various weights that may be removed from it in the process of operation, the document should contain information per items 3 through 6 of the above list, for each type of such removable weights. E.g., pipes, valves, pumps, etc. make up the load of the so-called «basic structure», and water (or other liquids) in this system is regarded as the «filler». The load data indicated in the design document should specify accordingly the type of such a «filler» (water, lub oil, diesel fuel, etc.). To simplify the subsequent information handling, the «fillers» are assigned numerical codes.

After the completion of this step of the design document check (for the completeness of information about the load), the document is checked for the reliability of information contained in it. E.g., the weight specified in a document can be checked by a simplified calculation as a function of any structural parameter (thus, to check the weight of deck plates one may use its function of the area). Co-ordinates of the centre of gravity of the entire structure (or installed equipment) can be approximately determined as co-ordinates of the centre of gravity of a uniformly filled geometrical body of a constant density.

The co-ordinates of centres of gravity of individual parts (or groups of parts) are checked selectively. When the calculation of the equipment load installed according to this design document is made «manually», they may check the correctness of arithmetic operations (e.g., summation of weights of individual parts or their weight moments).

After the completion of such (trivial) checks, the load as per the given design document can be included into the database on the submarine load balance of this project. The new load item is added to already checked equipment loads of the given structural group and the resulting value is compared against the specified limit. When all documents of the given structural group are completed, the final result is compared to the assigned limit to establish deviations of the weight and the weight moment. If the deviation exceeds the permissible value, the load for this structural group is revised. The aim of this revision is to find out reasons for such a deviation (whether it is the result of a design mistake or a consequence of some decisions directed toward equipment improvement in this structural group). The same procedure is applied if the document is not completed because the load limit has already been exceeded. In the detailed revision of structural documents developed for the given structural group, the loads per each document (or group of documents) are compared with similar loads estimated at previous design stages (for example, comparison of loads of the submarine light hull structures in the fore block with the similar loads obtained at the Engineering Design stage).

Construction Weight Control (Control by «Weighing»). In the process of submarine construction at a shipyard the load of equipment designated for installation is checked for its compliance with Detail Design documents. Practically, all equipment is weighed. The aim of this exercise is to guarantee trimming of the completed submarine and to meet requirements the submarine in terms of the value of the initial transverse metacentric height, as well as to be able to calculate the amount and the arrangement of the trimming ballast before launching the submarine.

Submarine construction weight control procedures include several types of weighing:

- part-wise (weighing of individual hull parts, equipment components, devices, etc.);
- assembly-wise (weighing of individual structural assemblies);
- section-wise (weighing of sections).