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ATOMIC-POWERED SUBMARINE DESIGN

V. M. Bukalov, et al

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The book will acquaint the reader with the technical problems of modern submarine building, and will shed some light on questions concerned with the design of atomic-powered submarines, propulsion and electronic equipment, systems and installations, weapons, and the equipment provided for making submarines habitable. The book was written from materials published in foreign technical and naval literature.

The book is intended for readers who are already familiar with naval shipbuilding fundamentals, and it can be used by engineering-technical workers in the shipbuilding industry, as well as by students in higher institutions of learning and in technical schools.

The index begins at Page 282.

p.3 **Foreword**

Foreign naval and technical literature is devoting a great deal of attention to problems of modern submarine building, and particularly to problems of designing and building atomic-powered submarines. The widespread introduction of nuclear missiles, of atomic propulsion, radio-electronics and cybernetics, has sharply increased the combat capabilities of the Navy and of its main striking force, the atomic -powered submarine fleet. However, the reports which have been published on this question are contradictory, uncoordinated, and often bear what is clearly the stamp of publicity. Works generalizing the experience gained in atomic-powered submarine building have not yet been published in the capitalist countries.

Our shipbuilding literature contains a great deal of material on atomic-powered submarines of the capitalist states. Included are the popular scientific books by I. A. Bykhovskiy, Atomnyye Podvodnyye Lodki [Atomic-Powered Submarines] (Sudpromgiz, 1957; 1963), and Atomnyye Suda [Atomic-Powered Ships] (Sudpromgiz, 1961), as well as the survey-type articles in the journal Sudostroyeniye [Shipbuilding]. 1960 saw the publication of the book by V. N. Gerasimov and V. F. Droblenkov, Podvodnyye Lodki Imperialisticheskikh Gosudarstv [Submarines of the Imperialist States] (Voyenizdat, 1960), a second edition of which was published in 1962, in which the authors pointed out the status and basic trends in development of the submarine fleet. However, the nature and trend of the book did not permit the authors to dwell in detail on technical questions of modern submarine building, or to cover with sufficient completeness the design features of submarines fitted with atomic-powered propulsion installations.

The authors of this book throw much more light on the technical problems which arise in the design and construction of atomic-powered submarines. The basis for the book is material published in generally available foreign publications, mainly American, between 1954 and 1963. A list of the literature
p.4 used is included at the end of the book, and references to concrete sources of information are given in the form of footnotes.

The authors have critically evaluated the foreign materials at their disposal, they have compared the data published in various of the sources, or they have made check calculations using widely known formulas and mathematical relationships (such as the formula for Admiralty coefficients, the "boiler" formula, the block coefficient, etc., for example).

The authors wish to express their deep appreciation to V. N. Kvasnikov, who reviewed the manuscript in its first draft and made a number of valuable comments. N. S. Grigor'yev, A. I. Vaks, E. B. Kodatskiy, E. Ye. Lysenkov, and A. A. Tokmakov, read individual sections of the book and were a big help to the authors.

The authors wish to express their particular gratitude to the Central Naval Library workers, whose day by day work simplified the authors' becoming familiar with the foreign literature.

The authors make no pretense of having fully exhausted the questions presented, and will accept with thanks all critical comments by readers.

Forward replies to Leningrad, D-65, Ul. Gogolya, 8, "Sudostroyeniye" Publishing House.

Chapter VIII

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Atomic Propulsion Installations

The development of atomic power engineering.

Despite the considerable improvement in diesel-electric installations during World War II, and in the first postwar years, the principal drawback submarines had, that of the need to come to the surface, or to periscope depth to recharge storage batteries, was not done away with. The low weight to size characteristics, as well as the comparatively low aggregate power of diesels and main drive motors, limited the further increase in the designed power for submarines. Internal combustion engines operating on a closed cycle, and steam-gas turbine installations of great power, made it possible to increase submerged speeds, but the range at full speed submerged remained limited.

Work on the building of steam-gas turbine installations for submarines had gone on in fascist Germany, and was continued in England, Sweden, and the United States in the postwar years. England built two experimental submarines of the Explorer-class, each of which was fitted with two steam-gas turbines rated at 4,000 hp, running on highly enriched (80%) hydrogen peroxide. Tests exposed the basic drawbacks of steam-gas turbine installations (high expenditure rates and costs for the hydrogen peroxide, reduction in turbine power with increased submersion depth, increase in danger of fire, and other problems) limiting their use in submarines.

American engineers too tested steam-gas turbine installations in SS346 but all work along these lines was stopped in 1950 as having no future prospects.

In December 1945, the U. S. Navy developed a program for the design and construction of an atomic-powered submarine fleet. General Electric and
47 Westinghouse, the giant American electrical machinebuilding firms, were brought in to work on the atomic propulsion installations (AEU). Combustion Engineering joined the other two later on. Construction of a land prototype of the AEU was begun in 1949, and was designated the S-1W (the first letter designating the class of ship for which the installation was intended, the number

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1. Engineer, Vol. 203, No. 5279, 1957.

the model sequence number, and the last letter the name of the manufacturer). The installation was designed as a two-loop system with a water-moderated, water-cooled reactor (a heterogeneous thermal neutron reactor with conventional chemically pure water under pressure as the moderator and coolant). The land prototype of the installation was built in 1953, and the first atomic-powered submarine, Nautilus, fitted with a type S-2W installation, was commissioned in 1955. This type of AEU is experimental, characterized by large weight and considerable volume for the propulsion spaces.

The United States was developing other types of reactors suitable for installation in submarines at the same time that the water-moderated, water-cooled reactor was in development. Seawolf was the first to get the S-2G, a heterogeneous intermediate neutron reactor using graphite as the moderator and liquid (molten) sodium as the coolant. The steam superheating system[1] sprang a leak during sea trials of Seawolf, the result of the corrosiveness of sodium. Attempts to fix the leak were fruitless, and the superheater had to be cut out. This reduced AEU power 20%. The S-2G was subsequently replaced by the S-2W-A, the prototype of which was installed in Nautilus.

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[1] The steam superheater in the land prototype of the AEU for Seawolf broke down after 1667 hours of operation.

The initial suggestion was to install fast neutron reactors with a helium coolant in Skate-class submarines. The American specialists were of the opinion that the use of gas turbine installations in a closed cycle would result in a considerable reduction in the weight and size of the machinery for submarines. However, the desire to commission all these ships as quickly as possible forced the Americans to install water-moderated, water-cooled reactors in these submarines, for they had proven themselves in operation.

Further development of reactors with water under pressure led to the building of the S-5W (fig. 98), and its modification, the S-5W-2. 52 reactors for the S-5W, including 41 for the S-5W-2, were built by 1 January 1962. The mass construction of installations of this type can be explained by their simplicity, the high degree of reliability, and the comparatively small weight and size. General Electric,[2] in addition to Westinghouse, concluded a contract with the U. S. Navy for delivery of reactors for the S-5W installations. p.248

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[2] Nucleonics, Vol. 19, No. 6, 1961.

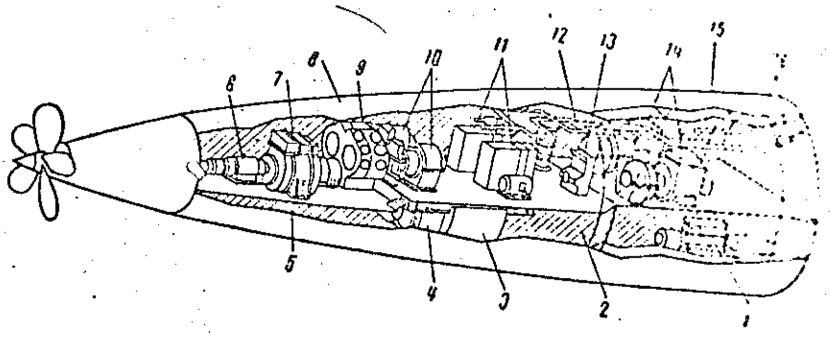

Figure 98. Arrangement of S-5W type propulsion installation in the submarine's spaces. 1 - diesel-generator; 2 - auxiliary equipment; 3 - reserve feedwater tank; 4 - main condenser; 5 - auxiliary equipment; 6 - propulsion thrust bearing; 7 - propulsion motor; 8 - engine room; 9 - main reduction gear; 10 - main turbines; 11 - switchboards; 12 - main steam line; 13 - control panel; 14 - turbine generator sets (according to other data, the turbine generator sets are located in the submarine's engine room and exhaust into the main condenser); 15 - auxiliary machinery space; 16 - steam generator cutout valves.

The United States continues work on improving propulsion installations using water-moderated, water-cooled reactors. These latter are considered as having the best prospects for improvement, at least for the next 5 to 10 years. A series of such installations with shaft horsepower ratings of 1500, 3000-4000, 6000-7000, 15000-17000, and 30000-40000, can be developed. The American specialists are of the opinion that combinations of AEU of this series of ratings can provide for any requirements advanced by atomic-powered submarine and surface naval shipbuilders. The upper limit for a single-shaft AEU is 60000-70000 hp.[1] Several such installations can be used if the need should arise to increase the power rating.

In the other capitalist countries work in the field of shipboard nuclear power engineering is still in the experimentation stage.

Figure 99 shows the arrangement of equipment in the spaces for the land prototype of the propulsion installation for the British submarine Valiant.

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[1] The Journal of Commerce and Shipping Telegraph, No. 41588, 1961.

Table 34. Characteristics of atomic propulsion installations for submarines and submarine cargo carriers for the capitalist states

	Type AEU	Type Submarine	AEU Specific Weight, kg/hp	AEU space consumption, hp/m^3	No. reactors	Thermal power, megawatts
1.	S-2W S-2W-A	Nautilus Seawolf	64-66	9.8 - 10.9	1	60-70
2.	S-2G	Seawolf	-	-	1	55-60
3.	S-3W S-4W	Skate Halibut	60-82	6.0 - 8.5	1	30-45
4.	S-4G	Triton	-	9.6 - 10.8	2	110-120
5.	S-2C	Tullibee	-	-	1	11-12
6.	S-5W	Skipjack George Washington Dreadnought (England)	52-58	10.0 - 11.2	1	60-65
7.	S-5W-2	Thresher Ethan Allen Lafayette	52-58	10.0	1	70-75
8.	S-5G	Jack	-	-	1	-
9.	-	20,000 dwt tanker	-	8.2	1	120
10.	-	40,000 dwt tanker	-	9.6	4	780
11.	630A	-	41-46	-	1	72
12.	-	-	-	-	1	74.4
13.	-	Valiant (England)	-	-	1	-
14.	-	Ore carrier Moby Dick (England)	82	-	1	150
15.	-	30,000 dwt tanker (Japan)	102	6.8	1	180

Table 34. continued.

	Coolant No. circulator pumps	Fuel enriched with U^{235}, %	Maximum parameters for coolant		Type main engines no. shafts x power at shaft, hp
			pressure kg/cm^2	temperature °C	
1.	water under pressure 6	20-40	140	260	geared turbine 2 x (6700-7500)
2.	sodium -	90	5-7	500	geared turbine 2 x 7500
3.	water under pressure -	20	140	246	geared turbine 2 x (3500 - 5000)
4.	"	-	165	280-290	geared turbine 2 x (15000-17000)
5.	"	-	-	-	turboelectric drive 1 x 3000
6.	water under pressure 7	40	160	280	geared turbine 1 x (15000-17000)
7.	water under pressure -	40	-	-	geared turbine 1 x (17500-20000)
8.	"	-	-	-	direct acting turbine 1 x -
9.	water under pressure 4	4	175	290	geared turbine 1 x 35000
10.	water under pressure 16	4	175	290	geared turbine 4 x 60000
11.	air -	-	21.8	760	steam turbine 30000
12.	helium	9	75	700	gas turbine 1 x 32000
13.	water under pressure 4	-	140	260	geared turbine 1 x -
14.	boiling water	-	-	-	geared turbine 1 x 50000
15.	water under pressure 3	1.7	-	-	geared turbine 2 x 22000

Table 34. Continued.

	Type turbine No. turbines	Working medium parameters		storage battery, no. elements capacity, ampere hours	No. turbogenerator sets x power, kw
		pressure, kg/cm^2	temp, °C		
1.	twin casing 2	18	220	126 -	4 x 650
2.	"	40-42	410-420	126 -	4 x 650
3.	- 2	15	-	126 -	2 x 800
4.	"	-	-	126 5500	4 x 1500
5.	turbogenerator 2	-	-	-	-
6.	single casing 2	23	240	126 * 112 - 6560	2 x 2000 ** 2 x 1800
7.	single casing 2	-	-	126 -	2 x 2250 ** 2 x -
8.	"	-	-	-	-
9.	"	30	-	126 -	2 x -
10.	twin casing 4	30	-	"	6 x 2500
11.	-	59.7	510	-	-
12.	-	75	700	-	-
13.	single casing 2	-	-	112 -	2 x -
14.	twin casing 1	-	-	-	-
15.	twin casing 2	25.5	250	-	3 x -

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*The denominatorcontains the figures for Dreadnought.

** The figure in the numerator refers to missile submarines, that in the denominator to torpedo submarines.

Table 34. Continued.

	No. diesel-generator sets x power, kw	No. converters x power, kw	Notes
1.	2 x 300	3 x 150	Core diameter 2.7 meters. Reactor diameter 4.57 meters. Land prototype S-1W. Maximum fuel element temperature 340°C.
2.	2 x 300	3 x 150	Land prototype S-1G. Maximum fuel elementtemperature 925±165°C.
3.	1 x 500	2 x 300	S-3W and S-4W differ in design of biological shielding.
4.	1 x 400	2 x 300	Distilling plant produces 60 tons/day. Land prototype S-3G.
5.	-	-	Reactor height 3.7 meters. Land prototype S-1C.
6.	1 x (400-500)	2 x 300	Reactor height 5.5 meters, diameter 2.45 meters, live steam consumption 82 tons/hour. Distilling plant produces 30 tons/day.
7.	1 x 600	2 x 300	Distilling plant produces 38 tons/day
8.	-	-	Reactor with natural coolant circulation.
9.	1 x -	2 x 300	Space requirement in reactor compartment 32-33 hp/m^3. Coolant circulation rate 10 meters/second.
10.	-	-	Condenser pressure 0.17 kg/cm^2.
11.	-	-	Initially developed as an aviation installation. Tested in Idaho in 1956-1960. Power can be stepped up t 50,000 hp.
12.	-	-	Core diameter 2.3 meters. Height 2.3 meters. Weight of charge 1.9 tons.
13.	2 x -	2 x -	Distilling plant produces 50 tons/day
14.	1 x 600	-	Two reserve diesels which can be coupled to the shaft through a reduction gear in the geared turbine.
15.	-	-	Weight of charge 7.3 tons. Live steam consumption 230 tons/hour.

p.249 Table 34 lists the principal characteristics of existing and planned propulsion installations for atomic-powered submarines and submarine cargo carriers in the United States and certain of the other capitalist countries.

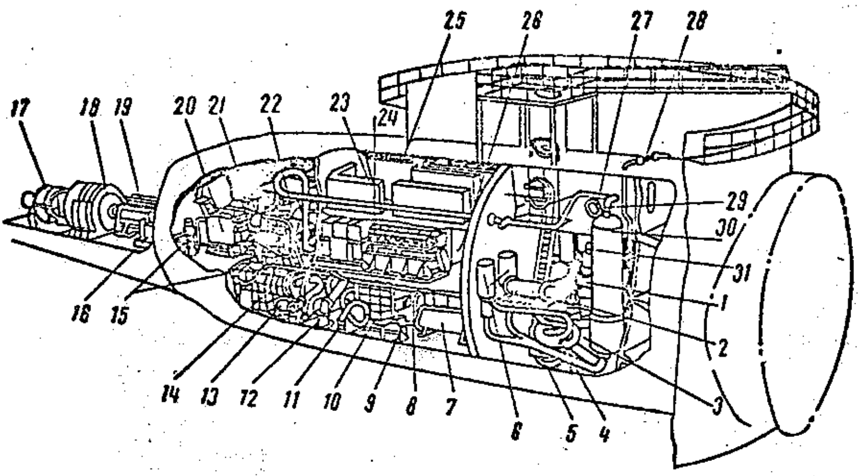

Figure 99. Arrangement of equipment in the compartments for the prototype of the propulsion installation for Valiant. 1 - reactor; 2 - stop valve in first loop; 3 - tank for primary protection; 4 - heat exchanger; 5 - pressure compensator; 6 - first loop circulator pump; 7 - feed water preheater; 8 - turbogenerator; 9 - auxiliary condensate pump; 10 - auxiliary condenser; 11 - auxiliary condenser circulating line; 12 - main condenser circulating line; 13 - main circulator pump; 14 - main condenser; 15 - sea water pump; 16 - scrubber in the regeneration system; 17 - propulsion thrust bearing; 18 - propulsion motor; 19 - clutch; 20 - refrigeration machinery; 21 - reduction gear; 22 - main turbine; 23 - auxiliary control board; 24 - diesel-generator; 25 - main control board; 26 - electrical distribution board; 27 - sight glass; 28 - emergency cooling heat exchanger; 29 - main steam line; 30 - steam generator; 31 - electric drive for the reactor control and protection system (SUZ).

Classifications and compositions of AEU.

The foreign scientific and technical literature[1] has accepted the following classifications for shipboard AEU in accordance with their design characteristics and the nature of the thermal pattern.

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[1] W. Crouch. Nuclear Shipboard Propulsion Installations. Gosatomizdat. 1961. Translated from the English.

According to type of atomic reactor: water-moderated, water-cooled; boiling; liquid metal cooled; gas cooled; organic liquid cooled.

According to thermal arrangements: single loop (in which the coolant is at once the working substance for the heat engine, the steam or gas .250 turbine, as well as the coolant); double loop; triple loop.

According to the type of working substance for the heat engine: steam turbine; gas turbine; hydrojet.

According to the method used to transmit power to the shaft: turbo-reduction gear; turbo-electric; direct acting turbine.

According to number of shafts: single, twin, and multi-shaft installations. An example of the multi-shaft installation is the AEU planned in the United States for the 40,000 dwt submarine tanker.

The atomic propulsion installation has been divided into two basic sections, the reactor section, and the mechanical section, regardless of type. The reactor section obtains thermal energy as a result of the reaction of fission of the nuclear fuel and the transfer of the heat obtained to the working substance. This section usually contains the reactor, the steam generators, or the gas heaters, the piping and the auxiliary machinery and installations. The reactor can be a steam producer, or a gas heater, depending on the type of working substance used.

The mechanical section converts thermal energy from the working substance into mechanical work for turning the propellers. This section includes the turbines with their condensers, mechanisms, systems and installations, the reduction gear or the electrical transmission system, the line shafting, and the propeller. The mechanical installation is called a steam- or gas-turbine one, depending on the type of working substance used.

The AEU aboard ship also includes the electrical equipment needed to feed the auxiliary machinery, the control instruments, the electronic devices, lighting, etc.

Most American atomic-powered submarines have, as part of the AEU, standby propulsion means so the submarine can maintain way in case of emergency, or if the reactor, or the main machinery, is shut down.

Finally, one of the most important parts of any atomic installation is the shielding to protect the personnel against injury, as well as the instruments and installations to protect the submarine against the radioactive radiation which occurs when the nuclear reactor is running.

Submarine propulsion installations are designed for operation under operating conditions much more severe that those experienced in atomic electric stations. In addition to maximum effectiveness, submarine installations must have the endurance and the ability to function under the various operating regimes encountered by submarines, under normal, and battle, conditions. The S-5W for example, [1] will continue to function at a constant list of p.251 15°, trim up to 30°, a roll amplitude of 60° and a period of 8 seconds, and a pitch with a period of from 4 to 60 seconds. The increasing endurance of submarines, and the sharp increase in operating range, have brought with them the need to increase the reliability of the propulsion equipment. This is why the strength of the main units in the installation has been increased, and why the principles of redundancy and splitting the power of main and auxiliary machinery are widely used.

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[1] Tidskrift i Sjovasendet, X,1961.

The requirements imposed on the maneuverability of submarine main propulsion installations are high. The time required to start up the AEU from the cold condition is 2 to 4 hours in modern submarines. It takes 1.5 hours to start up the reactor, while the turbines and turbo-generators can be warmed up in half an hour before the ship goes to sea. [2] A great deal of attention is also being given to such elements of installation maneuverability as reactor shut-down cooling time and change in turbine operating regimes, etc. Controllable pitch propellers are suggested for use on submarines in order to increase the maneuverability of turbine installations. An attempt to do so was made in England in 1953.

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[2] Nucleonics, Vol. 19, No. 9, 1961.

Weight and size characteristics are very important for submarine AEU. But American specialists are of the opinion that weight and size must not be reduced because the operational reliability of the equipment in the propulsion installation will deteriorate.

Reactor installation.

The principal element in the reactor installation is the nuclear reactor. Reactors found in U. S. Navy submarines in commission and building, as well as in similar British submarines, are heterogeneous types operating on thermal neutrons, which use enriched uranium as their fuel and distillate from natural water with a high degree of purity as the moderator and coolant (these are very often called water-moderated water-cooled reactors in the scientific and technical literature).

The fuel elements (TVEL) in submarine reactors are metal slabs of a uranium-zirconium alloy.[1] The TVEL is coated with an alloy, Zircoloy-2, which, in addition to the zirconium, contains as much as 1.4% tin and 0.18% other admixtures (chromium, nickel, iron, carbon), to prevent corrosion products from entering the coolant. The TVEL for the reactors in the S-3G and S-4G propulsion installations are made of thin sheets of metallic uranium rolled into spiral tubes. Shaping the elements in this form increases the
.252 surface for removing heat from the core, according to the American specialists.[2]

Rod-type TVEL, which are metal cylinders containing pellets of a ceramic nuclear fuel (usually UO_2), are envisaged for the submarine tankers in design. These TVEL have a high melting point and good resistance to corrosion. However, the greater fragility of the ceramic fuel results in a considerable reduction in the explosion resistance of the propulsion installation. This is why similar TVEL have not yet been used in combatant types of submarines in the capitalist states.

Enriched nuclear fuel is used in order to obtain compact, but adequately powerful, atomic reactors for submarines. The first core for the type S-2W installation was made of uranium 18 to 20% enriched with U^{235}. Enrichment was later increased to 40% and more. Enrichment in the S-1G and S-2G types is 90%. Slightly enriched (2 to 5%) fuel is proposed for use in submarine tanker installations. The weight of the fuel carried by the submarine tanker can reach a figure of several tons (the weight of the fuel for the AEU carried by the Japanese submarine tanker would be 7.3 tons, for example).

The uranium supply will make it possible for the submarine to cover great distances without recharging the core. The cores in the S-5W are designed to provide for steaming over 100,000 miles fully submerged, equal to 3500 to 4000 underway hours. The cores of the S-5W-2 provide for even greater range (about 140,000 miles). The TVEL in these cores have elongated fuel sections. At speeds 50 to 60% of full speed the range can be increased 2.5 to 3 times, while underway time increases to 20,000 hours. Average fuel burn-up in the

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[1] The Journal of Commerce and Shipping Telegraph, No. 41843, 1962.

[2] *Hansa*, Vol. 96, No. 8/9, 1959

reactor in the S-5W [1] is 10,000 megawatts/day/ton.

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[1] Nucleonics, Vol. 19, No. 9, 1961.

The cores of the S-2W are made in a monobloc construction, a design which makes refueling the reactor very much more difficult (the first refueling of Nautilus took several months). The individual replacement of fuel element clusters by removing the reactor cover became possible with the S-3W. In the S-4G the fuel elements are consolidated in a cassette which can be replaced without removing the cover. Special openings which are filled with removable plugs have been made for this purpose in the cover. According to press reports [2] this design reduces refueling time to 3 to p.253 4 weeks and provides for replacement of the core without the use of heavy-lift equipment.

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[2] Hansa, Vol. 96, No. 8/9, 1959.

A common design feature of US and British submarine reactors is the vertical positioning of the cores and the rod system for control and protection. The reactor housings are low-alloy carbon steel and are internally clad with stainless steel (304 in the United States). The equipment and piping in contact with the first loop coolant too is made of stainless steel.

British specialists rejected internal cladding of the reactor housing in their AEU design for Valiant, because of the highly complicated procedure involved in applying the coating. The reactor, and the first loop, are made of low-alloy steel containing 1% Cr and 0.5% Mo. Upon reacting with water this steel forms a sturdy magnetite film on the surface. The corrosion rate .25 is no more than 5 to 10 mg/dm^2 per month, [3] according to test results.

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[3] Nuclear Engineer, Vol. 7, No. 72, 1962.

Reactor covers are secured to the housings with standard flanges and securing bolts in a manner similar to that used in the Valiant reactor design, for example (fig. 100). A double gasket made of packing material, or a toroidal packing, inside which elevated pressure is maintained by a special system, is used with the cover installation. A feature of the S-5W is the use of a special connecting ring rather than the flanged connection for cover and housing.[4]

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[4] Nucleonics, Vol. 17, No. 9, 1959.

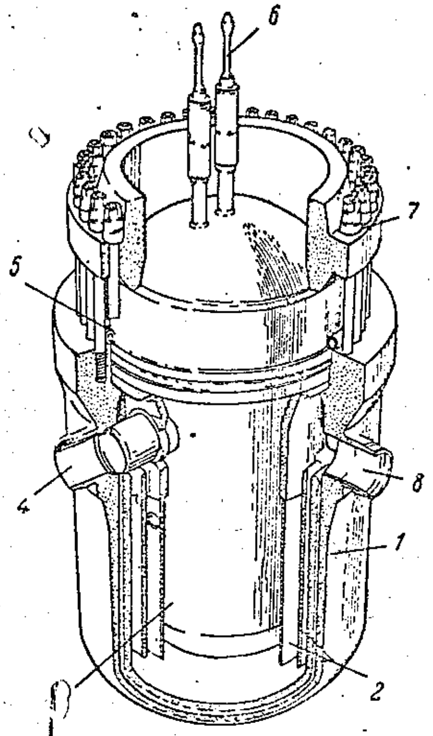

Figure 100. The reactor for the atomic-powered submarine Valiant. 1 - housing; 2 - thermal shield; 3 - core envelope; 4 - outlet connection; 5 - toroidal seal; 6 - rods in the reactor control and protection system (SUZ); 7 - clamping flange; 8 - outlet connection.

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The core casing is a cylinder located inside the reactor housing and contains the TVEL [fuel elements] and controls the movement of the control rods. The top and bottom of the casing are closed in by base plates which simultaneously support the casing within the housing.

The control and protection system (SUZ) is designed to automatically regulate the power produced by the reactor in accordance with the steam consumption, as well as to shut the reactor down in case of emergency. The SUZ rods (control, shim, and safety) are made of materials well able to absorb neutrons, such as boron steel, cadmium, or hafnium (the latter was used for the SUZ rods in Valiant).

The SUZ control rods have an electromechanical rack drive providing for their insertion into the core at comparatively low speeds. In case of emergency tripping the rods are "killed" by a hydraulic, or other fast-acting drive, as a result of which the nuclear reaction can be discontinued instantaneously. Valiant also has a system for the forced addition of salt, a neutron absorber, to the first loop coolant in order to stop the reactor in case the SUZ rods cannot be inserted in the core because of damage.[1]

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1. North East Coast Institute Transactions, V, 1962.

Fission products accumulate in the core during reactor operation. Certain of them, particularly xenon-135, are more intensive captors of the neutrons than is the nuclear fuel and they act as harmful absorbers in the system, destroying the neutron balance in the reactor. This phenomenon is called "poisoning" the reactor. Shim rods, which move out of the core as the fission products accumulate, are installed in the reactor core in an effort to cope with poisoning. A certain equilibrium concentration of poisons is established in the reactor with the passage of time. When the reactor is shut down the neutron flow dies out and the xenon accumulation increases considerably at first. Poisoning[2] can make the next start of the reactor impossible for several hours.

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2. Since the increase in the xenon-135 concentration occurs as a result of the decay of iodine-135, which begins to accumulate the instant the reactor stops, this poisoning phenomenon is often called the "iodine pit."

American specialists are of the opinion that if submarine reactors are not to be poisoned by xenon, it is necessary to:

operate at power settings close to the maximum, since this will result in but slight xenon accumulations during the transition processes;

p.255 hold reactor power at a level within 1% of full for several days after the ship has tied up, since this will lend itself to xenon burn-up;

put an excessive amount of fuel in the reactor in order to more successfully overcome the consequences of poisoning.[3]

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3. W. Crouch. Nuclear Shipboard Propulsion Installations. Gosatomizdat. 1961. Translated from the English.

The steam-generating installations in the AEU for modern submarines are made on a double-loop arrangement. Each loop for the first loop coolant consists of the steam generator, several circulator pumps, the piping, and the fittings. The thermal diagram for the AEU in Valiant envisages an additional loop for emergency reactor shut-down cooling with natural circulation of the coolant through the overboard cooler (fig. 101).

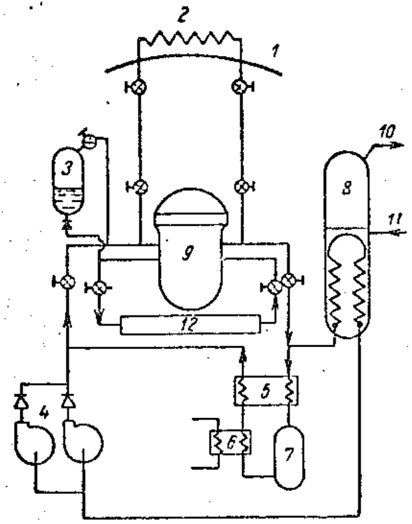

Figure 101. Schematic of the steam generating installation in Valiant. 1 - pressure hull; 2 - heat exchanger for emergency reactor shut-down cooling; 3 - pressurizer; 4 - first loop main circulator pumps; 5 - regenerative heat exchanger in the system for purifying first loop water; 6 - cooler; 7 - ion-exchange filter; 8 - steam generator; 9 - reactor; 10 - steam; 11- feed water; 12 - second loop of the first loop.

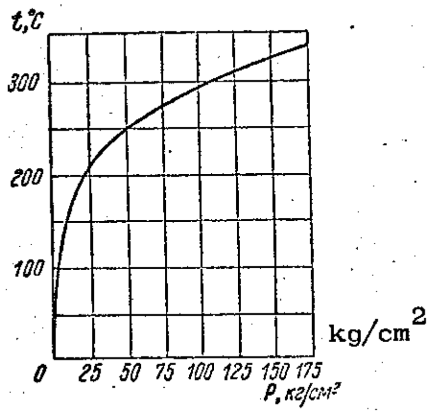

Figure 102. Curve showing the dependence of temperature of beginning of water boiling, t, on pressure in the reactor housing, P.

A special pressurization system maintains high pressure in the loop, retaining the liquid, aggregate, condition of the water (fig. 102). The basic element in the system is the steam pressurizer shown in Figure 103.

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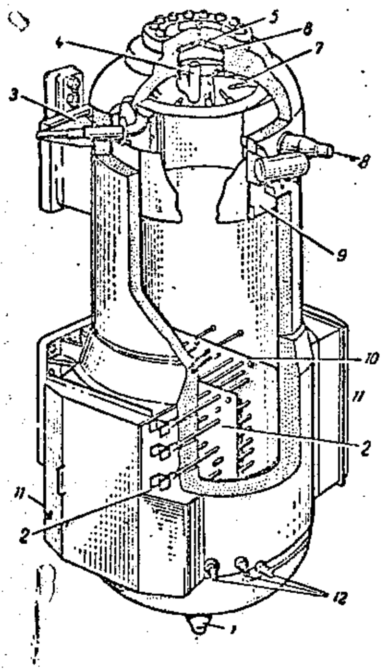

Figure 103. Pressurizer.1-flexible connection; 2 - electric heater; 3 - water feed line to spray nozzle; 4 - connection for safety valve; 5 - packing diaphragm; 6 - support ring; 7 - water spray nozzle; 8 - fitting for installation for level determination; 9 - protective water screen; 10 - support baffle; 11 - terminal block; 12 - fittings for connecting level indicator.

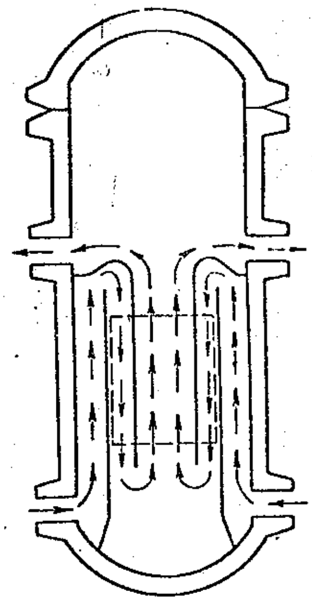

Figure 104. Three-pass diagram of flow of coolant in the reactor housing.

Increased pressure in the first loop increases the secondary steam parameters, and thus the installation efficiency. However, this adds weight to the AEU and makes ensuring the air-tightness of the first loop more difficult.

The three-pass arrangement for the flow of water (fig. 104) in the S-5W installation is an innovation as compared with the old single-pass systems. The principal advantage of the new arrangement is that the amount of water pumped through the core is reduced because of the improvement in the heat transfer from the fuel to the coolant, bringing with it a reduction in the size of the circulator pumps needed. Foreign specialists feel that the complexity of the interior design of the reactor, as well as the increase in the activity of the water in the first loop resulting from the water being in the core
257 longer, are drawbacks of the three-pass arrangement. This latter circumstance requires more careful purification of the water to remove corrosion products and radioactive materials, and this involves the installation of a special water treatment system into which 0.05 to 0.2% of the consumption of first loop coolant is diverted.

Judging from published data, most submarines will not have deaerators in the first loop water treatment system. Instead, the water will be treated in demineralizers consisting of several ion-exchange filters. The resins in the ion-exchangers chemically purify the water, removing dissolved impurities and corrosion products. The radioactive particles which are not dissolved in the water are caught by porous mechanical filters. Water circulation in the water treatment system comes about as a result of the difference in pressures between the first loop and this system, while the coolant parameters can be reduced as the coolant passes through the series of coolers and throttle valves.

According to U. S. Navy Bureau of Ships specifications, the salinity of the water in the first and second loops of shipboard atomic propulsion installations must not exceed 0.1 mg/liter, while the hydrogen index must be within a range of pH = 6 to 8. Water salinity can increase to 2.3 mg/liter[1] at the inlet to the ion-exchange filters.

Submarine steam generators are vertical heat exchangers with natural water circulation in the second loop. The use of natural circulation has increased the reliability of the equipment as compared with single-pass

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[1] Navy Civil Engineer, Vol. 4, No. 1, 1963.

steam generators, or generators with forced circulation of the secondary coolant. Design-wise, the steam generators are in the form of two-pass heat exchangers with tube sheets. The U-shaped tubes for the circulating water in the first loop are rolled and welded to the sheets. The steam generators in the S-2W installation are single-pass with sinusoidal bends in the tubes to compensate for temperature expansion. Valiant's steam generators have double tube sheets, and the U-shaped tubes are welded on the inner side.[1] A general view of this equipment, as well as a schematic of how the tubes are welded, is contained in Figure 105.

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[1] The Journal of Commerce and Shipping Telegraph, No. 41843, 1962.

The steam collectors and separators, which are single-stage (cyclone type in American submarines) or two-stage (the first stage cyclone, the second of the herringbone type, in Valiant), are located in the upper part of the steam generators. The separators maintain the moisture of the live, saturated steam at no more than 0.25%.[2]

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[2] Nucleonics, Vol. 17, No. 9, 1959.

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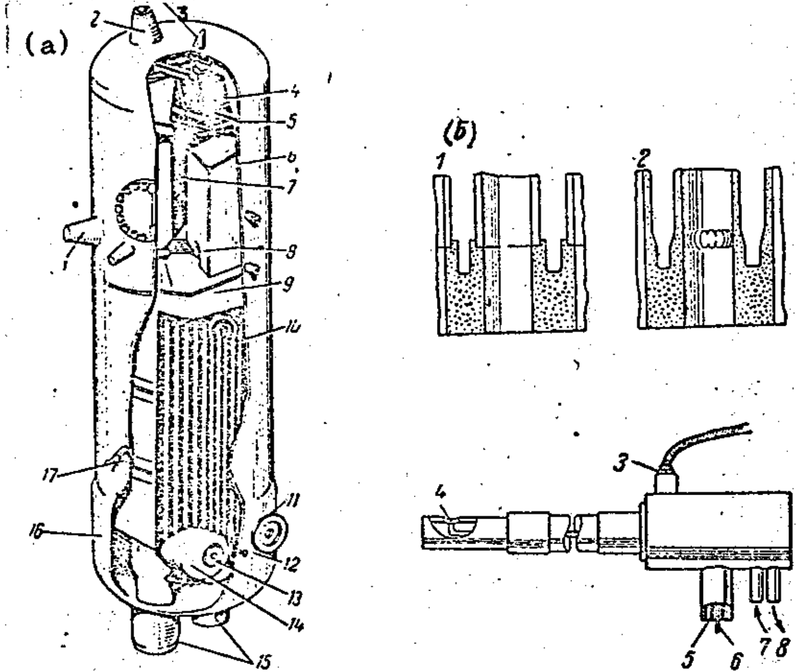

Figure 105. Valiant's steam generator and the schematic for welding the tubes. a - steam generator: 1 - feed water inlet; 2 - live steam outlet; 3 - to safety valve; 4 - herringbone separator baffles; 5 - separating baffles; 6-cyclone separator; 7 - condensate collector; 8 - feed collector; 9 - outlet chamber; 10 - tube nest; 11 - port in steam generator housing; 12 - thermocouple; 13 - port to water collector; 14 - primary coolant collector; 15 - fittings for coolant inlet and outlet; 16 - steam generator housing; 17 - flow rate measuring device; b - schematic for welding the

tubes and section of a welded head: 1 - preparing for welding; 2 - completed weld; 3 - flexible drive from controller; 4 - electrode; 5 - inert gas feed; 6 - electric power supply; 7 - cooling water supply; 8 - cooling water discharge.

Two or three main circulator pumps, and one standby, are installed for each autonomous loop in the first loop. In the S-5W installations the standby pump can be cut in on either of the two coolant loops as needed. AEU circulator pumps for submarines (fig. 106) have AC drive motors. A distinguishing characteristic of the pumps is the airtight seal for the rotor of the electric motor, thus precluding the possibility of water leaking through the shaft gland.

In the first of the atomic-powered submarines the speed of the drive
motors was changed by reducing the AC frequency from 60 to 30 cycles (with
turbogenerators) or 17 cycles (with motor-generators). The electric motors
59 for the pumps in the S-5W installation have two windings. The winding for
high speed is connected to the turbogenerator busbars, while that for low
speed is connected to the busbars of the submarine's reversible converters
(see the section on "Electrical Equipment").

Auxiliary systems are used to cool individual units in the first loop and the shield. In one of these systems (internal) circulation is of distillate which gives up its heat to the sea water in the coolers in the external cooling system. The arrangement of subsequent loops is designed to prevent salting up the coolant in the first loop, or the carrying out of radioactivity.

All radioactive equipment in the reactor installation is installed in an uninhabited section of the reactor room and encased in the shields provided. Also located here are the control and measuring devices and the remote controlled valves (hydraulic and electromagnetic) used to monitor and control the installation. There are no more than 24 such valves in *Valiant's* installation.

Reactors other than water-moderated, water-cooled are used in submarines. *Seawolf*, for example, initially used an installation in which the reactor was cooled by liquid sodium. The design work on this AEU assumed that the high heat-transfer coefficient of the metal would make it possible to obtain working steam with higher parameters. In theory, the steam parameters can be

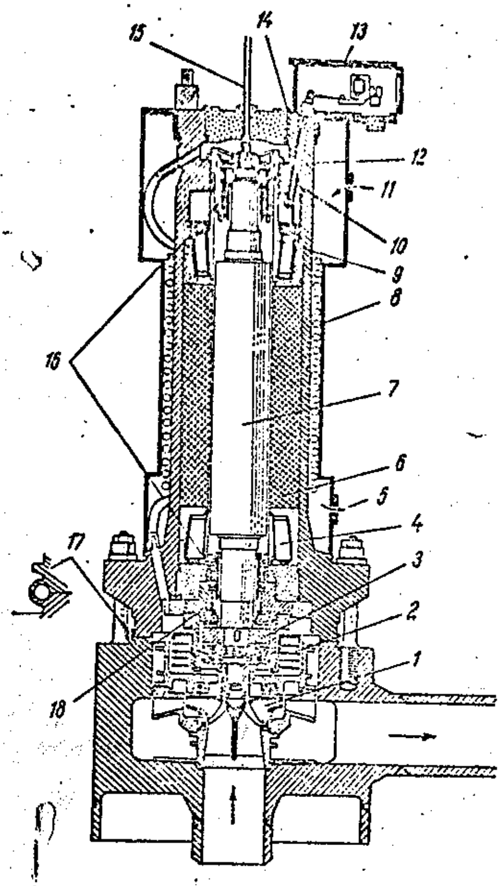

Figure 106. Main circulator pump in the first loop in Valiant. 1 - pump impeller; 2 - heat shield; 3 - thrust bearing; 4 - stator winding; 5 - cooling water outlet; 6 - stator; 7 - rotor; 8 - stator cooling tubes; 9 - water-protective envelope; 10 - electric power supply; 11 - cooling water inlet; 12 - cooling pump; 13 - connection box; 14 - 17 - toroidal seal; 15 - water blowdown; 16 - supporting bearings; 18 - thrust bearings.

p.260 raised to 46kg/cm^2 and 455°C, while the pressure in the first loop is not in excess of 5 to 7 kg/cm^2.[1] There are a number of practical difficulties involved in the use of sodium as a first loop coolant. The great chemical activeness of the alkali metals causes intensive corrosion, as well as a considerable temperature drop in the reactor (reaching 250°C) which increases the stress in the material.

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[1] W. Crouch. Nuclear Shipboard Propulsion Installations. Gosatomizdat. 1961. Translated from the English.

A two-loop design was used in the S-2G installation, with the steam generators having double-walled tubes with a liquid metal circulating inside, and the second loop water circulating outside. The space between the walls was filled with a potassium-sodium alloy which transferred the heat from the primary coolant to the working substance. The steam superheaters for the reactor installation were of similar design. Electromagnetic type pumps were used as circulator pumps in the first loop. Their capacity can be regulated by changing the voltage.

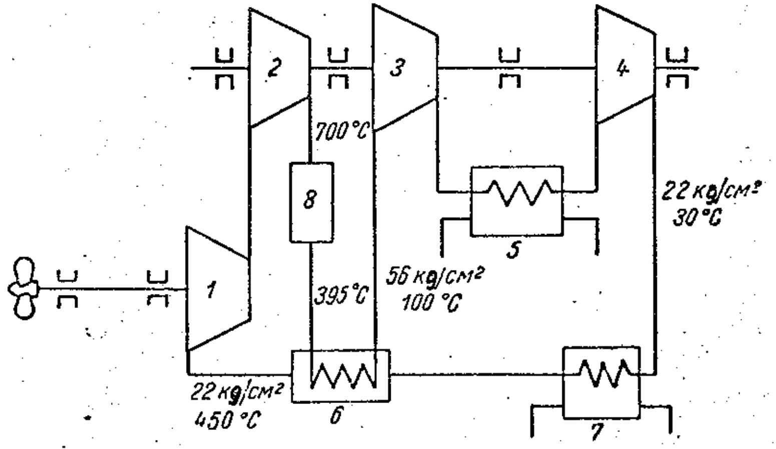

Figure 107. Schematic arrangement of an atomic-powered gas turbine installation rated at 22,000 shaft hp. 1 - LP turbine; 2 - HP turbine; 3 - HP compressor; 4 - LP compressor; 5 - intermediate cooler; 6 - regenerator; 7 - cooler used prior to cutting in main plant; 8 - reactor.

Boiling reactors are envisaged for the propulsion installations in the British submarine cargo carrier design, and the Swedish submarine tanker design. 261 Reactors such as these considerably simplify the AEU thermal system, but the increased radioactivity of the live steam makes it necessary to protect the ship's turbine installation, as well as the reactor. Moreover, the reduction in the water density during the steam formation process reduces the water's effectiveness as a moderator, leading to increased weight and size of the atomic reactor.

Reactors with an organic coolant-moderator (terphenyl, for example), are very similar in their principal schematic to water-moderated water-cooled reactors, but the dimensions of their cores are smaller, and the pressure in the first loop is lower. Absence of fuel element corrosion, and the low level of activation of the coolant in the neutron flux, are the chief advantages of these reactors. American specialists include the high cost of the organic liquid, its decomposition, and polymerization during irradiation and heating, among the disadvantages.

The gas-cooled reactor is one of the types with the greatest future prospects. According to foreign specialists atomic-powered gas turbine installations using a single-loop arrangement (fig. 107) should be 20 to 25% lighter than AEU with water-moderated water-cooled types of reactors. The gas parameters (as high as 50 to 75 kg/cm^2 and 700 to 800°C) provide greater efficiency for the thermal cycle of the propulsion installations. It is possible that, after careful development, a single-loop AEU with high-temperature reactors and gas turbines will be successfully used in submarine shipbuilding.

Biological shielding.

Nuclear reactor operation results in intensive radioactive radiation, and the greatest danger to submarine personnel, as well as to the various instruments and equipments, is neutron and gamma radiation. The basic requirements, effectiveness, lightness, compactness, must be taken into consideration in the resolution of problems concerned with biological shielding for submarines.

The shielding for land-based atomic installations and for cargo ships is usually quite heavy. The total weight of the shielding in Savannah, for example, is in excess of 2,100 tons.

American designers used the so-called "shaded" method of locating the shielding in order to reduce the weight of submarine installations. The protection for the reactor room is thus divided into complete and partial. The complete shielding separates the reactor room from the living spaces and the control stations in the submarine. The first of the atomic-powered submarines, which had living spaces forward and aft, had complete shielding
p.262 installed on both transverse bulkheads of the reactor room. The weight of this shielding was 30 to 35% that of the entire propulsion installation. In submarines of later build only the forward bulkhead of the reactor room has a complete shield. The after bulkhead and the deck have a partial shield because personnel are only in compartments adjacent to the reactor room for limited periods of time (up to 8 hours a day). The partial shield is usually half the thickness of the complete one.[1]

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[1] B. Price et al. Protection Against Nuclear Irradiation. IL, 1959. Translated from the English.

The sides of the reactor room are covered with a comparatively thin layer of shielding material, so it is possible to inspect the submarine's hull in drydock when the reactor is shut down. Moreover, it is specified that the radiation penetrating beyond this layer when the propulsion installation is in operation, and the radiation reflected from the sea water, will not be dangerous for the inhabited spaces in the ship, and will not in the slightest reveal the presence of the submarine.

In the *Skate*-class, with S-4W installations, the horizontal protective deck in the reactor room has been replaced by a cylindrical passageway through the space. However, according to reports contained in the foreign press,[1] this type of shielding has not resulted in any reduction in the weight and size characteristics of propulsion installations.

Biological shielding can be divided into primary and secondary,[2] in accordance with the location of the source of the radiation. The primary shielding, which directly surrounds the reactor core, must so weaken the flow of fast neutrons that there will be no great activation of the coolant in the second loop, and reduce to a minimum the gamma radiation which accompanies the capture of neutrons in the secondary shielding. Moreover, the primary shielding should reduce the residual radiation to a safe level, thus making it possible to enter the reactor room some time after the reactor has been shut down. According to information published on the subject, the primary shielding for submarine reactors is in the form of water tanks surrounding the core. The top and sides of the tank are clad with sheet lead. In *Nautilus*, for example, the diameter of the tank used for primary shielding is 4.5 meters, while the core diameter is 2.7 meters.

The secondary shielding surrounding the active equipment in the reactor
installation reduces the flow of neutron and gamma radiation to safe levels
.263 and prevents radioactive contamination of the air in living and working spaces.
The outfitting of reactor installations makes use of the principles of self-
shielding; less active equipment covers the more active (the reactor, the

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[1] *Nucleonics*, Vol. 17, No. 9, 1959.

[2] T. Rockwell. "Specifications for Reactor Shielding," in the book "Shielding for Transport Installations with Nuclear Engines," IL, 1961. Translated from the English.

ion-exchange filters) in the direction of the inhabited spaces.[1]

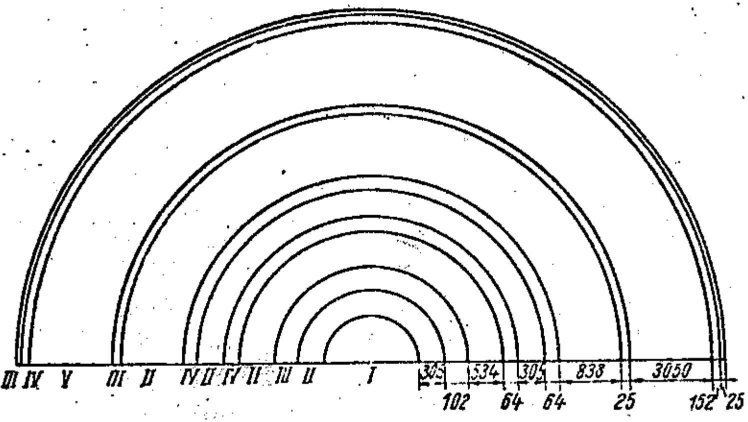

Figure 108. Schematic diagram of a metal-hydrogen shield (dimensions in mm). I - core; II - water; III - steel; IV - lead; V - first loop equipment.

Submarine shielding material is a composite, that is, it contains heavy and light elements. Metal-hydrogen shielding is usually used, since it provides for least weight and volume per unit area.[2] A typical schematic of a metal-hydrogen shield is shown in Figure 108. Steel and lead are the components used to shield against gamma radiation. Lead plates, manufactured by the American firm Federated Metals Division, are used in <u>Skate</u>, <u>Triton</u>, <u>Skipjack</u>, and other of the atomic-powered submarines. This firm uses a special casting technique which results in a high quality metal, one free of bubbles and porosity. Despite its great density, lead used in the metal-hydrogen shield in atomic-powered submarines provides for a gain in the battle against weight of at least 20% as compared with steel.

The lead shielding is combined with hydrogenous materials in order to weaken neutron radiation. Widely used in shielding is water, as well as
p.264 substances with higher hydrogen contents per unit volume, such as polyethylene and polystyrene. Diesel fuel supplies are included in the shielding aboard American atomic-powered submarines.

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[1] B. Price et al. "Recommendations for computing the shielding for atomic propulsion installations," in the book *Shielding for Transport Installations With Nuclear Engines*, IL, 1961. Translated from theEnglish.

[2] B. Price, et al. Metal-Hydrogen Shielding. *Ibid.*

Imperial Chemical Industries (USA) has developed a new material, boroplast, which effectively shields men and equipment against neutron radiation and reduces the captured gamma-ray output, as compared with water or polyethylene.[1] Boroplast is a polyurethane plastic, to which polyethylene or nylon granules containing up to 10% boron carbide have been added. It is produced in sheets, 3 to 25 mm thick, and 915 mm wide. Almost 23 tons of these sheets are used in each atomic-powered submarine.

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[1] Financial Times, 20/IV, 1961.

Boral,[2] a metal and ceramic composition, made of finely dispersed particles of boron distributed in aluminum, is used in submarine AEU shielding. The weight relationship is 1:1 for both metals. Boral is produced in 6 mm thick sheets.

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[2] Kopal'man. Materials for Nuclear Reactors. Gosatomizdat, 1962. Translated from the English.

The British firm, Associated Lead Manufacturers, has proposed a combination shielding material called densiten, which is a mechanical mixture of lead powder and polyethylene. Six parts by weight of lead and one part by weight of polyethylene yields densiten with a density of 3.9 grams/cm^2. The material is readily fashioned and secures well to metal surfaces.[3]

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[3] Financial Times, 13/VII, 1961.

Examples of thicknesses of the basic materials for the shielding which provide a ten-fold attenuatin of radioactive radiation, are listed in Table 35. Required in practise is an attenuation on the order of 10^8 to 10^9 for neutron, as well as for gamma, radiation. The total thickness of the primary and secondary shields can thus be several meters (in Seawolf, for example, the shield is 2.4 meters thick).[4]

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[4] Our Navy, No. 6, 1958.

The calculations for the shielding of an AEU are extremely time-consuming.[5] What makes them particularly complicated is the possibility of radiation "leakage" as a result of local heterogeneity in the material (the shield can include hull structures, such as frames, bulkhead stringers, the beams in tank frames, etc.). The radiation thermal, and chemical resistances of the materials used must also be taken into consideration. The shielding sometimes includes a special layer of thermal insulation, or a cooling system for the shield elements is envisaged.

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5. The process involved in making the calculations for the shield is described in the article by B. Price, et al, "Recommendations for Shielding Calculations," published in the book Shielding for Transport Installations With Nuclear Engines, IL, 1961. Translated from the English.

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Table 35. Examples of thicknesses of materials for shielding providing a ten-fold attenuation in radiation

Field of use for material	Material	Density t/m^3	Thickness, cm		
			A	B	C
Protection against fast neutrons	Polyethylene	0.9	96.4	20.3	60.9
	Water	1.0	96.4	22.8	60.9
	Diesel fuel	0.8	122.0	22.8	76.2
Protection against gamma radiation	Steel	7.8	11.7	14.0*	9.1
	Lead	11.3	5.1	20.3*	5.3
Combination protection	Concrete	2.3	44.5	25.4	30.5
	Barium concrete	3.5	23.9	19.1	19.1

A - Gamma radiation from the core of an operating reactor (energy 7 mev);
B - Fast neutrons; C - Gamma radiation from fission products (energy 2 mev).
* with the addition of a layer of water, polyethylene, or fuel 30 to 45 cm thick.

Computers are widely used in scientific-research and design organizations in the United States to make the calculations for submarine shielding.

Propulsion Plant

It is difficult to superheat steam in an AEU with water-moderated water-cooled reactors because of the relatively low temperature of the primary coolant, so the steam-turbine plants in submarines run on saturated steam at 200 to 250°C and at pressures from 12 to 25 kg/cm^2. An increase in steam parameters is planned for the future, but the increase will be slight because an increase in the pressure of the live steam to more than 30 to 35 kg/cm^2 will worsen the weight characteristics of installations of this type.[1] AEU with liquid metal reactors have higher steam parameters. The steam-turbine plant in Seawolf is supposed to use superheated steam at 410 to 420°C at a pressure of more than 40 kg/cm^2.

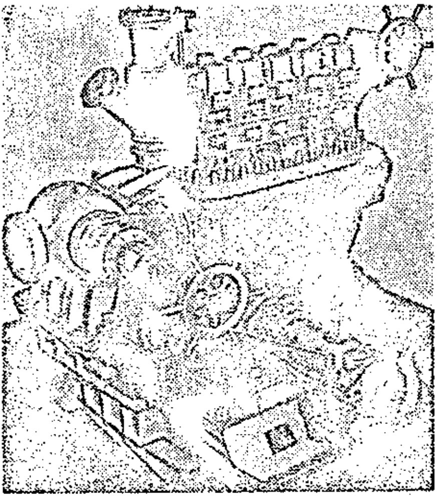

Figure 109. The main turbine in Dreadnought.

The main turbines for the first atomic-powered submarines had two casings, consisting of an HP turbine and an LP turbine. The astern turbine was located in the LP turbine casing. The low initial steam parameters made it imperative to dry the steam as it expanded in the turbine, so a steam separator was installed between the HP and LP turbines, and some of the main turbine stages were fitted with moisture separators.

Single-casing steam turbines (fig. 109) are used in the new atomic-powered submarines. Every submarine has two turbines operating on a single propeller shaft through a two-stage reduction gear in order to increase plant survivability, as well as in order to reduce the length of the engine room.

Submarine main condensers, since they are cooled by sea water, can withstand a pressure corresponding to the designed diving depth. They can hold a vacuum equal to 100 to 130 mm mercury column at a sea water temperature of 18°C. [2] Exhaust steam from the main turbines, and from the ships service generators, flows into the main condensers in Nautilus. There are auxiliary condensers as well, and these serve the turbo-generators for the reactor installation. The standby condensers take the steam (by-passing the turbine) in event of a reduction in power required for the geared turbine unit in the

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1. Transactions SNAME, Vol. 65, 1957.

steam-turbine installation (fig. 110). In the submarines of later build the steam is dumped into the main condensers directly.

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2. Tidskrift i Sjovasendet, X, 1961; Shipbuilder and Marine Engine-Builder, Vol. 68, No. 641, 1961.

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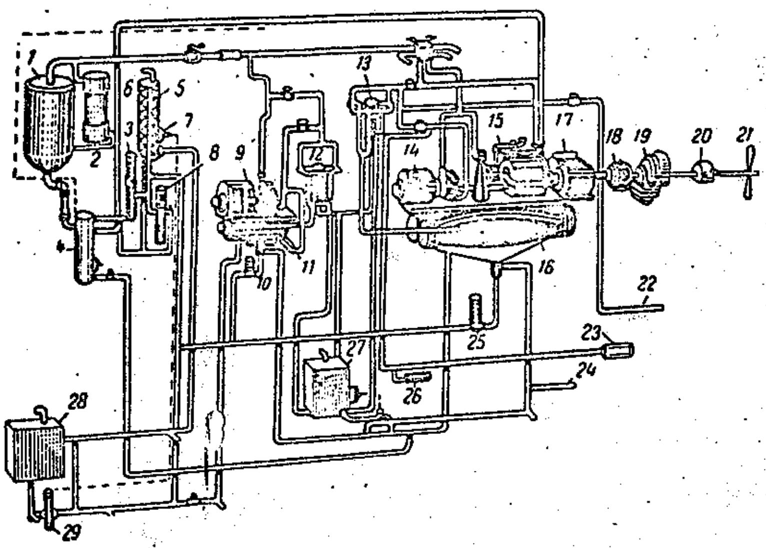

Figure 110. Schematic diagram of the steam-turbine plant in Nautilus (starboard side). 1 - separator; 2 - condenser for emergency steam dumping; 3 - auxiliary feed pump; 4 - feed water preheater; 5 - overflow; 6 - water-level regulating tank; 7 - level regulator; 8 - main feed pump; 9 - turbogenerator for reactor room busbars; 10 - condensate pump; 11 - lube oil cooler; 12 - air ejector; 13 - main air ejector; 14 - ship's service turbogenerator; 15 - main turbine; 16 - main condenser; 17 - reduction gear; 18 - disengaging clutch; 19 - electric drive motor; 20 - thrust bearing (sic); 21 - propeller; 22 - to evaporator plant with a production rate of 15 tons of distillate per day; 23 - lube oil cooler for line shafting; 24 - from evaporator plant; 25 - main condensate pump; 26 - main lube oil cooler; 27 - collection tank; 28 - reserve feedwater tank; 29 - distributor-feed pump.

A serious drawback in submarine condensers is the low resistance to corrosion possessed by their tube nests. Dual tube sheets were used in the condensers in Valiant in order to overcome this drawback.

Most atomic-powered submarines use a two-stage geared reduction to transmit power from the main turbines to the propeller shaft. Submarine reduction gears have quite a high coefficient of contact pressure on the

working surfaces of the teeth; for submarine tankers 7 kg/cm^2 for the gear
wheel in the first, and 9 kg/cm^2 for the gear wheel in the second stage of
the reduction. These coefficients are 14 to 19 and 12 to 14 kg/cm^2, respect-
ively, for atomic-powered combatant types of submarines.[1] The increase in
the specific loads on the teeth came about as a result of the use of high-
hardness materials in manufacturing the gear wheels, as well as from an in-
268 crease in the accuracy and the cleanliness with which the teeth were finish-
ed, and from the corresponding corrections made to their profiles.

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[1] Transactions SNAME, Vol. 62, 1954.

Tullibee has electrical transmission of power to the shaft, instead of a geared reduction. American specialists are of the opinion that this sort of replacement should reduce propulsion plant noise, but the weight and size of the plant will go up quite a bit.

As has already been noted, the United States is developing a direct-drive steam turbine for the new atomic-powered submarines. The stator (this designation can only be provisional in this particular case) and rotor in this turbine rotate in different directions and transmit rotation to coaxial propellers. Tests of coaxial propellers were conducted on Albacore in 1962-1963.

The auxiliaries for the steam-turbine plants in submarines have electric drives. The use of auxiliary steam turbines running on live steam taken from the main geared-turbine unit is proposed for driving the circulator and feed pumps in the American submarine tankers.

Despite a number of design features, steam and feed water leaks from the second loop in submarine AEUs are quite numerous. These leaks are taken as equal to 0.25% of the consumption of live steam in the main steam line of a propulsion plant[1] when designing modern submersibles. Submarines have distilling plants which can produce 30 to 60 tons of distillate a day for use in replenishing feed water losses. Distillate salinity[2] is not in excess of 1 to 2 mg/liter for sea water salinity of 32 to 35 mg/liter.

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[1] Transactions SNAME, Vol. 67, 1959.

[2] Proceedings of American Power Conference, III, 1960.

All equipment associated with the steam turbine plants in the Nautilus, Seawolf, Skate, and Halibut classes is located in one space. An additional compartment for auxiliaries has been added between the reactor and engine rooms in ships of later build.

Submarines can use closed cycle gas turbines, as well as steam-turbine plants. Rolls-Royce, the British firm, is developing a marine atomic-powered gas turbine plant with a shaft horsepower of 15,000. One design feature has the turbine, compressor, and heat exchanger in a single casing, cylindrical in form, and 2.5 meters in diameter. Access to the gas turbine installation (GTU) under shipboard conditions is precluded. The unit is designed for long, p.269 casualty-free operation without opening, and can be replaced with a new one at base in case of need. Compressors and turbines are positioned in the casing with their shafts symmetrical (fig. 111), while the heat exchangers are arranged in two tiers around the compressors and turbines. The use of compressed air is proposed for the working medium in the GTU.

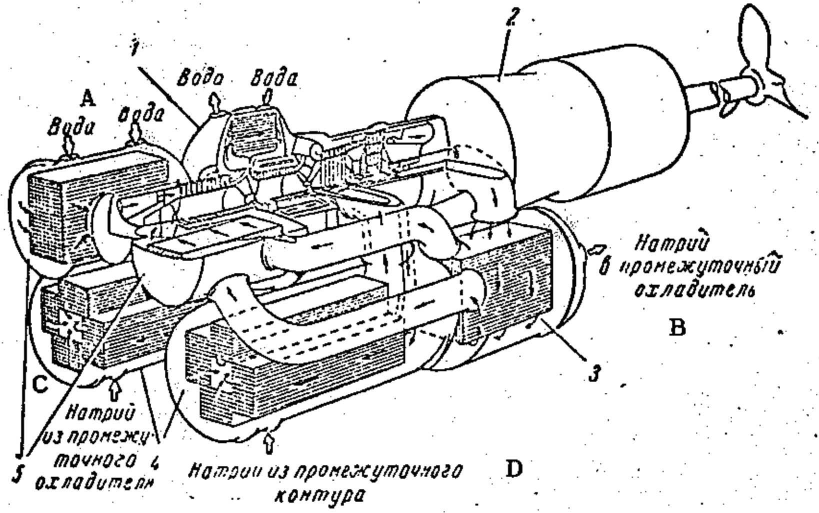

Figure 111. Grouping of the atomic-powered gas turbine installation rated at 15,000 hp by Rolls-Royce. 1 - intermediate cooler; 2 - reverse reduction gear; 3 - port regenerator; 4 - preheater; 5 - preliminary coolers; A - water; B - sodium to intermediate cooler; C - sodium from intermediate cooler; D - sodium from intermediate loop.

Standby propulsion.

Electric propulsion is planned as the standby in atomic-powered submarines in the United States and in England. Slow-speed electric drive motors, direct current, are connected to the line shaft for this purpose. They can be supplied with power from the turbo-generators (through converters), from diesel-generators, or from storage batteries. When the electric motor is in use the main geared-turbine unit is disconnected from the line shaft by a disengaging clutch which, in addition, copes with possible breaks in the line shaft caused by the shifts taking place in the shock-mounted geared-turbine unit.

The foreign literature contains no information on the power ratings of the propeller drive motors for atomic-powered submarines, but the installation in the submarines of a single group of storage batteries and a diesel-gener-
270 ator installation rated at from 400 to 600 kw provides the basis for assuming that the electric motor rating is 300 to 500 hp at 220 to 250 volts. This will provide for a speed of 5 or 6 knots. The diesel-generator installed in Skipjack-class provides a range of 2,000 miles.

The main suppliers of diesel-generators for the American fleet are General Motors and Fairbanks Morse, [1] firms which have developed a series of horizontal and vertical submarine engines featuring small size and low specific weights (1.8 to 5.4 kg/hp). Submarine diesel-generators have devices permitting operation at periscope depth. Back pressure at the exhaust can be 0.35 to 0.40 kg/cm^2.

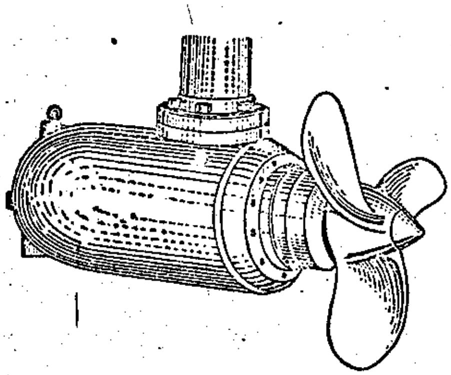

Figure 112. Standby electric motor for an atomic-powered submarine

Standby propulsion, in the form of two submerged electric motors driving three-bladed propellers [2] were installed in George Washington in 1961, as a result of the increased vulnerability of the propeller-rudder complex of single-shaft submarines. The standby electric motors (fig. 112) are located in the

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[1] Curtiss-Wright is supplying a type 12V-142, 900 hp, diesel for generator drive aboard the Lafayette-class submarines.

external space (most probably in the vicinity of the auxiliary machinery room) and can, in case of need, be extended beyond the limits of the external shell by special, extendable spars similar to the stocks of the rudder-roll dampers for surface ships. The spars also provide for rotating the electric motors around the axis of the spar through 360°. Future plans call for fitting all U. S. Navy atomic-powered submarines in commission and building with similar installations.

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2. Machine Design, Vol. 33, No. 17, 1961.

The design of the standby electric drive installations is similar to that of the motors for the active rudders manufactured by Pleuger (FRG).

p.271 Characteristics of the submerged electric motors for the active rudders include:

Motor rating, hp	100	150	250
Dimension, mm			
motor diameter	470	470	650
motor length	1170	1270	1420
length of housing	2090	2210	2515
propeller diameter	700	800	950
RPM	950	950	720
Motor efficiency, %	86	87	87
Power factor	0.83	0.85	0.83
Installation weight, kg	850	1000	2000
Propeller thrust, moored, kg	1500	2100	3400

Propeller pitch in the 150 hp installation is 490 mm, the blade area ratio 0.58. Submerged electric motors for submarines have increased resistance to explosions and the capacity to run at great depths. The United States, according to press reports, [3] is producing submersible, AC, electric motors which will be able to run at pressures up to 140 kg/cm^2.

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3. Marine Engineering/Log, No. 3, 1962.

Standby propulsion of the future will have compact atomic-powered propulsion installations. American specialists have proposed a project for a motor similar to the above with a gas reactor with a thermal power rating of 6 mw. The distinguishing characteristic of the installation is is the small size of the reactor core (diameter 28 cm, length 25 cm). All AEU equipment has been installed in a separate gondola. Shaft horsepower is 1600 hp, specific weight 2 kg/hp.

Electrical Equipment

Primary current aboard atomic-powered submarines in the U. S. Navy is 60 cycles AC. Voltage at the generator terminals is 450 volts. Once the single engine (AEU) was built, the submarines began to use AC, which made it possible to reduce the size and weight of the electrical equipment, and to increase its reliability.

Steam-turbine driven 3-phase synchronous generators are the sources of AC in submarines. The rating of submarine generators can change from 650 to 2250 KW in one unit. Most submarines have horizontal, self-contained, turbo-generators. Generators in the atomic-powered missile submarines are rated at 2250 KW at 3600 rpm and a power factor of 0.8. <u>Thresher</u>-class has vertical generators, so a more rational arrangement of equipment in the AEU compartments is possible.

`72 A 220 volt DC system is retained in the atomic-powered submarines to supply the electric drives of installations requiring regulation over a wide speed range, as well as by way of having a standby power source for electric drive and providing electric power for AEU machinery for starting and cooling down the reactor. The DC sources are storage battery and a diesel-generator.

The battery in U. S. Navy atomic-powered submarines consists of 126 cells. Cell dimensions were 356 x 457 x 1170 mm, weight 450 kg, in the first such submarines. The batteries are the acid-type, connected in series. Rated voltage for a battery is 250 volts. Voltage drops to 175 volts when discharge is at a high current rate. The capacity of the Type MAY-51A storage battery installed in <u>Triton</u>[1] is 5,500 ampere-hours. The Bell Telephone Company, in conjunction with the U. S. Navy's Bureau of Ships, has developed a lead-calcium battery for the new atomic-powered submarines which does not liberate harmful gases when used. Capacity can go as high as 7,000 ampere-hours. Since storage batteries in atomic submarines are comparatively seldom charged, American designers have done away with the cooling water system used in the diesel-electric submarines. This simplified the design of the batteries and resulted in a considerable saving of funds for building the submarines.

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[1] Funi-no Kagaku, Vol. 14, No. 8, 1961.

A battery of 112 cells has been installed in *Dreadnought*. The jars are glass plastic instead of ebonite. The capacity of the *Dreadnought's* acid batteries has been increased to 6,560 ampere-hours at the 5-hour discharge rate (as opposed to 4,730 ampere-hours for the diesel-electric submarines built in the postwar years). The new batteries can take up to 300 charge-discharge cycles.

The use of silver-zinc cells can result in increasing battery capacity while reducing their weight and size, according to foreign specialists.[1] Batteries such as these have been installed in the American diesel-electric submarines *Barracuda* and *Albacore*. That in *Albacore* consists of 440 cells with a total weight of 200 tons. Battery capacity is 20,000 to 25,000 ampere-hours. The installation of silver-zinc batteries is also planned for the deep submergence research submarine *Aluminaut*, which will carry 77 cells, the capacity of which will be 32,500 ampere-hours.[2] The chief drawback of p.273 silver-zinc cells is the high cost, approximately 10 times more than that of conventional lead storage batteries.[3]

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1. Machine Design, Vol. 35, No. 9, 1963.
2. Ordnance, No. 249, 1961.
3. Our Navy, Vol. 55, No. 2, 1960.

Comparative characteristics of acid and silver-zinc storage batteries include:[4]

	Battery	
	Acid	Silver-zinc
Voltage, volts	1.5 - 2.1	1.0 - 1.8
Specific energy:		
kw/hour/ton	33 - 44	70 - 130
kw/hour/m^3	90 - 120	200 - 270

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4. Design News, Vol. 17, No. 23, 1962; Naval Engineers Journal, Vol. 74, No. 4, 1962.

Diesel-generator installations are used in all American atomic-powered submarines, in all probability. Initially there was a reduction in the power ratings of their diesel-generators from 600 kw for *Nautilus* to 500 kw for *Skate*-class, and to 400 kw for *Triton*-class, *Skipjack*-class, and *George Washington*-class, but later on the ratings of the diesel-generators were increased to 600 kw in *Lafayette*-class.

Converters, rated at 150 to 300 kw, are used to convert AC into DC (for charging storage batteries from the turbo-generators, for example), or from DC into AC (to run machinery in the reactor cooling system off the batteries). The converters consist of DC motors and synchronous generators. The generators can also be run as synchronous motors. When this is the case the motors become generators and supply power to the DC busbars.

Atomic-powered submarines also have high (400 cycles, 120 volts) and low (15 cycles, 450 volts) frequency nets in addition to their AC and DC nets, as well as a low-voltage DC (28 volts) net. These nets supply the radio, radar, sonar, and other electronic equipment on board, as well as the circulator pumps in the first loop of the AEU at low speeds (current at a frequency of 15 cycles). High-frequency AC is obtained from 3-phase converters (motor-generators) rated at 25 kva in torpedo submarines, and 40 kva in the missile submarines. *Skipjack* and *George Washington* classes have three such units installed. The requirements imposed on the electric power systems in missile submarines have been stiffened; voltage and frequency fluctuations may not exceed 0.5% of rated values.

.274 Noiseless semiconductor instruments are used to rectify and convert electrical current in the systems aboard atomic-powered submarines. A compact silicon rectifier, rated at 48 kw (64 volts, 750 amps) is used in the oxygen generator, for example. A similar rectifier supplies the independent excitation windings for the turbo-generators. Semiconductor instruments rated at 60 kw (75 kva) which convert DC from the battery to AC at 400 cycles and 355 volts, are developed for *Thresher* and *Lafayette* classes. Voltage and frequency oscillations must not exceed 1%.

Atomic-powered submarines have a great many consumers of electric power. The major consumers include the machinery in the propulsion installation, its systems and devices [1] (150 kw and more), the lube oil pumps (30 kw), and others. In *Skate* and *Thresher* classes the sonar requires 14.8 and 54.2 kw, respectively, the radar 1.76 and 3.8 kw, communications equipment 5.9 and 19.3 kw, computers 2.3 and 5.85 kw, navigation gear and control equipment 1.14 and 2.85 kw. Equipment used for living purposes in atomic-powered submarines draws 30 kw for galley equipment, 10 kw for the electric heaters in the air heaters, 10 kw for the laundry driers, etc.

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[1] Here, and henceforth, the required electric power for one machine will be indicated.

Some idea of the extent to which atomic-powered submarines are saturated with electrical equipment can be obtained from the following figures. Nautilus has almost 73 km of electric cables. Seawolf has 63 electric motors rated at better than 1 hp, and their weight is 12.2 tons. Relatively low motor weights are achieved by the use of organo-silicone insulation (the same motors using conventional insulation would weigh almost 17 tons). The missile carriers have even more powerful electrical equipment. George Washington-class has in excess of 130 km of electric cabling, and 118 electric motors.

All consumers of electric power in atomic-powered submarines can be divided into two groups, according to importance. One group is automatically disconnected in event of emergency shut-down of the reactor, while the other (vitally important consumers, such as the electric motors running pumps in the reactor shut-down cooling system, the hydraulic systems, and the like) continue to function, using power from storage batteries, or from the diesel-generator installation.

p.275 The lighting system in atomic-powered submarines is fed from 3-phase, 450/120 volt transformers. The 120 volts is used for incandescent lamps with thicker filaments which have greater mechanical strength. This voltage is less dangerous to personnel aboard ship in event of damage to the electrical network. Submarines use incandescent and fluorescent lamps rated at 20 watts for general lighting, and 8 watts for local lighting of desks, bunks, etc. The lighting circuits in each compartment are fed from two feeders, each independent of the other.

Automatic breakers, types ACB (large, air), AQB (small, air), and ALB (low voltage), are installed in order to protect the elements in the electrical network against overloads and short-circuits.

The electrical power systems in atomic-powered submarines are controlled from a main distribution switchboard located in the AEU control station compartment. Design-wise, the switchboard is made in the form of two vertical rack-type cabinets, each 600 x 500 x 1900 mm. The frames of the racks are made of aluminum alloys. Group distribution panels are installed in the submarines in addition to the main distribution switchboard. The distribution panel for the electric motors for the circulator pumps in the first loop are located in the upper part of the reactor room, for example. The panels measure 360 x 530 x 1960 mm.

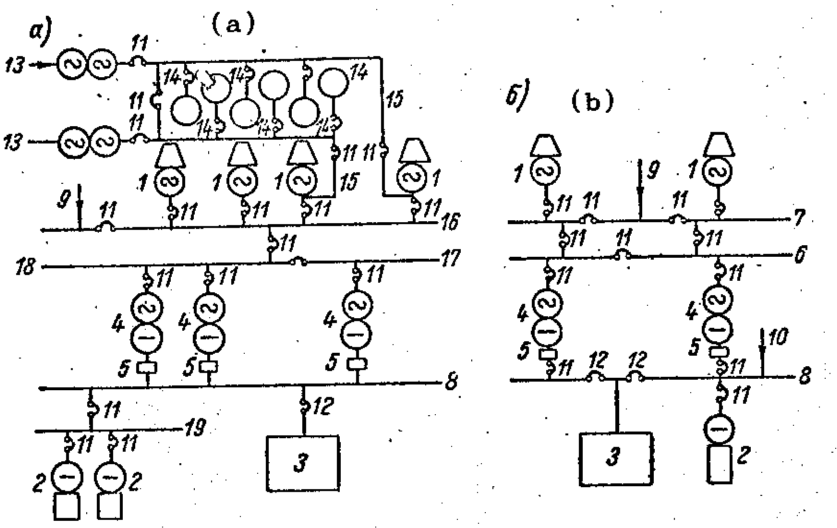

Figure 113. Principal schematic diagrams of generation and feeding of current in Nautilus (a) and Skate (b). 1 - turbo-generator; 2 - diesel-generator; 3 - storage battery; 4-reversible converter; 5 - DC electric motor starter; 6 - AC busbar for consumers in group designated as of first importance; 7 - same, for secondary importance group; 8 - DC busbar; 9 - AC from shore power; 10 - DC from shore power; 11 - circuit breaker; 12 - battery breaker; 13 - from busbar for primary consumers in reactor room; 14 - first loop circulator pump electric motors; 15 - busbar for circulator pump electric motors; 16 - busbar for secondary consumers; 17 - busbar for primary consumers in reactor room; 18 - same, engine room; 19 - electric propulsion busbar.

.276 The principle schematic diagram of generation and feeding of current aboard Nautilus and Skate-class is shown in Figure 113. Nautilus has special turbo-generators for supplying the electric motors for the circulator pumps in the first loop of the AEU. The turbo-generators in Skate-class are not distinguished as to purpose. Nor are there any special busbars for the engine and reactor rooms in these submarines. All of which serves to reduce considerable the weight of the electrical equipment. Similar electrical systems are used in most American atomic-powered submarines.

American designers are of the opinion that by increasing the AC frequency they will be able to reduce the weight and size of the electrical equipment and increase its reliability. Under particular consideration is shifting lighting to 400 cycle AC. The possibilities of widespread use of semiconductor instruments for the production and conversion of electrical energy are under study. Moreover, the problem of using light, synthetic materials to manufacture insulation and fittings for submarine electrical equipment is being solved.

Research Work.

In addition to the scientific-research and experimental-design work in the field of further improvements in existing types of AEU, the capitalist countries, primarily the United States, are engaged in seeking new ways in which to convert atomic or chemical energy contained in "fuel" into mechanical energy for submarine propulsion.

One of the most important tasks is considered to be the creation of a small-size AEU, suitable for installation in small displacement submarines. The development of an engine such as this is part of the SNAP program in the United States. American specialists are suggesting that test stand trials of an AEU known as SNAP-4 will begin in 1965. This installation is designed for cosmic ships, for self-contained hydroacoustic buoys to be set out in the ocean, and, probably, for ASW submarines. The electric power from the SNAP-4 installation will be 1,000 kw, and the specific weight of the shipboard version of the AEU will be 18 kg/hp. The installation will include a boiling reactor and a turbo-generator. The whole installation should fit in a space 4.9 to 5.0 meters long, and about 2.2 meters in diameter. It is assumed that
p.277 the specific weight of the SNAP installation will be reduced to from 3 to 7 kg/hp in the future.

The U. S. Navy is considering a proposal made by General Atomics, which expressed its readiness to begin development of an atomic engine for a bathyscaphe. The firm's specialists are of the opinion that the electrical power developed by an installation such as this would be between 25 and 50 kw, and that its dimensions would be such that it could be installed in bathyscaphes, or in midget submarines.

Electric drive motors obtaining their energy sources from fuel elements, thermionic converters, or thermoelectric generators.

The use of thermionic converters in propulsion installations for submarines would make it possible to do away with such huge units as the turbines, turbo-generators, condensers, etc., as well as to increase the installation's operational reliability, the result of the elimination of moving parts. Thermionic converters will make it possible to build practically noiseless machinery (given the condition that removal of heat in the reactor will be the result of natural circulation of the coolant). Because it is most important to obtain high power per unit volume and weight of installation in submarine shipbuilding, thermionic converters are a desirable application, even though their efficiency is low (14 to 15%). A thermoelectric generator, remote from the reactor, or a steam turbo-generator, can be combined with thermionic elements in order to increase reactor effectiveness. And use of the former will still retain the noiseless machinery feature, while use of the latter will provide for greater propulsion installation efficiency.[1]

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[1] Nuclear Science and Engineering, Vol. 10, No. 2, 1961.

As distinguished from thermionic converters, thermoelectric generators are proposed for use primarily as power sources for auxiliary machinery, combining them with atomic-powered steam turbine and gas turbine installations. Foreign specialists are of the opinion that the use of the heat which, in modern installations, is carried by the sea water through the air-conditioning system, will considerably increase installation efficiency without causing any deterioration in weight and size characteristics for the installation. The U. S. Navy is planning the development of a thermoelectric generator with an efficiency of about 4.5% in the near future.

Fuel cells are electrochemical current generators which convert the chemical energy of a fuel directly into electrical energy. The fuel used p.278 in the cells can be hydrogen, lithium, sodium, and various of the hydrocarbons, such as methane, propane, ethyl and methyl alcohol. Oxygen, chlorine, or compounds of these elements, are most often used as the oxidizer. Fuel cells are divided into Oxygen-hydrogen, oxygen-sodium, chlorine-sodium, etc., depending on the type of fuel and oxidizer used.

The electrochemical "combustion" of the fuel takes place in a cell in the unit, which is filled with an electrolyte (fig. 114). The anodic process is one in which the molecules of fuel (positive ions) make a transition in the electrolyte, giving up the corresponding number of electrons.

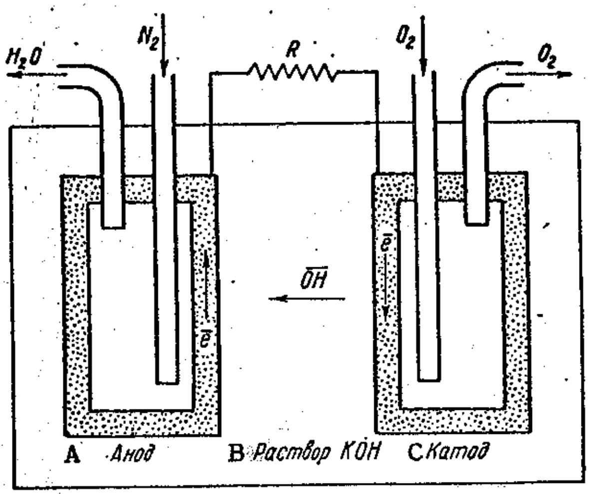

Figure 114. Schematic of an oxygen-hydrogen fuel cell.
A - Anode; B - KOH solution; C - Cathode.

The molecules of the oxidizer acquire these electrons at the cathode, and they too flow through the electrolyte, but in the form of negative ions. Thus, an ordered movement of electrons takes place in the external circuit, while the positive and negative ions, combining in the electrolyte, form reaction products. Water is the reaction product in the oxygen-hydrogen fuel cell. The electrodes are given a porous structure in order to increase the reaction rate, and, as a result, current strength.

The most valuable property of fuel cells is high efficiency, which can theoretically reach 90%. Table 36 lists the calculated energy magnitudes
p.279 resulting from the "combustion" of 1 ton of reacting substances (fuel and oxidizer) in fuel cells of various types.[1]

Fuel cells, in addition to high efficiency, have the following advantages: they radiate little noise in operation; they are explosion-proof; they are highly reliable, simple to operate, and economical; they have a comparatively low specific weight, and are small in size.

These advantages have attracted the attention of foreign, mainly American, naval specialists to fuel cells. There are a number of firms in the United States working on creating fuel cells for industry (Union Car-

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[1] RCA Review, Vol. 22, No. 2, 1961.

Table 36. Theoretical energy productivity for low-temperature fuel cells

Топливо A	Окислитель B	Химическая реакция процесса C	D Энергия, выделяющаяся при «сгорании» 1 *т* реагирующих веществ, *квт-ч*
H_2	O_2	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	3640
C	O_2	$C + O_2 \rightarrow CO_2$	2470
CH_4	O_2	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	2690
C_3H_8	O_2	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$	2820
$C_{10}H_{22}$	O_2	$C_{10}H_{22} + 15\frac{1}{2} C_2 \rightarrow 10CO_2 + 11H_2O$	2840
Na	O_2	$2Na + H_2O + \frac{1}{2} O_2 \rightarrow 2NaOH$	2090
CH_3OH	O_2	$CH_3OH + 1\frac{1}{2} O_2 \rightarrow CO_2 + 2H_2O$	2420

A - fuel; B - oxidizer; C - chemical reaction of the process; D - energy produced by the "combustion" of 1 ton of reacting substances, kw/hour

bide, Standard Oil, Lockheed, and others). General Electric is developing a propulsion installation with oxygen-hydrogen fuel cells for an ASW submarine, the design for which is being handled by the Electric Boat Division's Design Office.[1] Maximum power for the installation will be 600 kw; volume almost 600 m^3. The fuel elements will take up 270 m^3 of this volume in the compartment (the weight of a battery is 150 tons). It is suggested that these magnitudes will be reduced to 230 m^3 and 115 tons, respectively, in the future. The oxygen and hydrogen carried will enable the propulsion plant to operate for 360 hours at reduced power (200 kw) and for an additional 10 hours at maximum power. The volume of the space needed to carry the fuel and oxidizer is 160 m^3.

Another American firm, M. B. Kellog Company, has concluded a contract with the Bureau of Ships for the development of oxygen-sodium fuel cells for a shipboard propulsion installation. When the work is completed the company will have an experimental installation rated at almost 100 hp. It is assumed[2] that the specific weight of this installation, with fuel and oxidizer supply, will

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[1] Transactions SNAME, Vol. 69, 1961.

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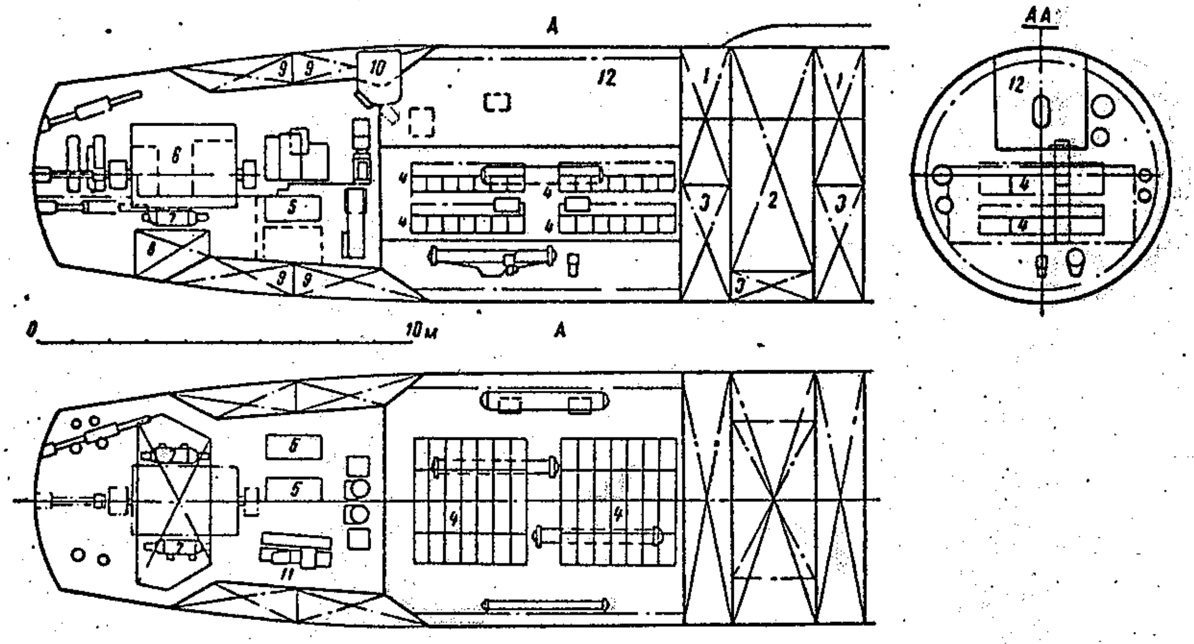

Figure 115. General arrangement of propulsion installation spaces in a submarine with fuel cells. 1 - liquid O_2 tank; 2 - liquid H_2 tank; 3 - substitution tank; 4 - fuel cells; 5 - 35 kw converter; 6 - main drive motor; 7 - 20 kw converter; 8 - fuel tank; 9 - main ballast tank; 10 - rescue hatch; 11 - air-conditioning installation; 12 - passageway.

p.281 be no greater than 0.9 to 1.4 kg/kw/hour.

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2. Machine Design, No. 6, 1961.

The U. S. Navy planning for the near future includes the construction of several small submarines fitted with propulsion installations with fuel cells. Vice Admiral Hayward, Deputy Chief of Naval Operations, has said that the fuel cells for the first of these submarines will use oxygen and methyl alcohol, but that their efficiency will not be in excess of 50%. Submarines with fuel cells will be less noisy that atomic-powered ones, they will be about 1/3d the size of standard atomic-powered submarines, and will cost 30 to 50% of that for the latter. It is assumed these new submarines will not completely replace those with nuclear propulsion installations, and that they will be used for antisubmarine defense.[3]

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3. Product Engineering, Vol. 32, No. 17, 1961.

The future use of water jet engines, which will provide the submarines with high speeds (up to 100 knots and more), is suggested. Work along these lines is already in progress. Boeing Aircraft, an American firm, announced the development of an atomic-powered jet engine for submarines. According to Boeing the principle of operation of this engine is similar to that of the air-breathing turbojet engine, but the jet will be steam and water.[1]

"Aerojet," another American firm, is developing a type EX-8 ramjet engine for atomic-powered submarines. The main drawback of all water jet engines is the extremely low efficiency (from a fraction of a percent to a few percent). The efficiency can be improved in the future to a figure of 20 to 30% by using special mixers which will provide for the agitation of the primary jet by the secondary flow it causes.

United States scientific-research organizations are studying the possibilities of using the electromagnetic principle for submarine propulsion.[2] One of the designs proposed by American scientists is a double-hulled submarine, .282 along the entire length of which runs a fore-and-aft channel of annular cross section, open at both ends. The walls of the channel will carry AC solenoids, so that a "traveling" magnetic field will be created from bow to stern. This field will result in the appearance in the sea water of an electrical field and of electrical eddy currents, the interaction of which with the magnetic field will result in the development of a force which will coincide in direction with the movement of the magnetic field. This force will set up continuous displacement of the water in the channel, creating a jet stream, and providing for submarine movement.

According to the American scientists, it should be understood that there is little liklihood of using electromagnetic force for submarine propulsion. Without dwelling on the design complexities of a project such as this, it is enough to say that it would require magnetic induction in the water of 6,000 gauss in order to move a submarine almost 200 meters long at 10 knots. There is no question of the fact that induction of this scope is much too high for the volumes of the propulsion installations which have been considered. Moreover, the magnetic field developed will be a strong indication of the submarines whereabouts, and will bring to naught all the efforts made to increase the secrecy of the whereabouts of submarines.

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[1] Financial Times, 10 March 1960.

[2] Journal of Ship Research, Vol. 5, No. 4, 1962.

Appendix

83 The international system of units, SI, was introduced in the USSR on 1 January 1963. There are a great many organizational and technical difficulties connected with the changeover to the new system of units. The state standard (GOST) permits the use of non-system units during the transition period. The relationship between units in the SI system, and those outside the system, which will be encountered in the text are listed below.

Magnitude	Unit in the SI system	Abbreviation for unit	Non-system units of measurement
Speed	meter/second	m/sec	1 knot = 0.515 m/sec
Angular velocity	radian/second	rad/sec	1 revolution/second = 2π rad/sec
Force	Newton	N	1 kg = 9.81 N
Pressure (mechanical stress)	Newton/square meter	N/m^2	$1 kg/cm^2 = 98.1 \cdot 10^3 N/m^2$ $1 kg/m^2 = 9.81 N/m^2$ 1 atmosphere $= 1.013 \cdot 10^5 N/m^2$
Work, energy, amount of heat	joule	j	1 kg/m = 9.81 j 1 calorie = 4.187 j 1 large calorie = 4186.8 j
Power	watt	w	1 hp = 735.6 w (sic) 1kg/m/sec = 9.81 w
Magnetic induction	tesla	tl	1 gauss = 10^{-4} tl

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