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CHAPTER III

MATERIALS FOR THERMAL INSULATION AND PROTECTION

This chapter discusses various materials having the following common properties: ability to block the transfer of thermal energy, or offer a high resistance to heat flow (thermal insulation), or prevent the action of thermal fluxes of high specific density on the object being protected (thermal protection), etc. /185*

Such materials are widely employed in many areas of technology, particularly in shipbuilding, as thermal insulation materials providing protection from thermal shocks, fire retardants, and other materials of this type.

A brief discussion of some of these materials follows.

III.1. HEAT-INSULATING MATERIALS

1. General Properties

Heat-insulating materials have low thermal conductivity, i.e., high heat resistance, and are used for maintaining certain thermal conditions (preventing the penetration or removal of heat).

Although the thermal conductivity index λ is a decisive factor determining the heat-insulating properties of a material, the practical applicability of the material requires a number of other properties; for example, the specific weight, mechanical strength, combustibility, hygroscopicity, bioresistance, nontoxicity, technological workability, etc.

Therefore, although there are many materials with low values of λ, the number of high-quality heat-insulating materials is relatively small.

There is no single classification of heat-insulating materials, since, depending on the selected classification criterion, most diverse groups of them can be obtained. For example, heat-insulating materials may be subdivided according to the following basic criteria:

(a) nature of the material - organic, inorganic (mineral) and mixed materials;

(b) character of the raw materials used in the preparation of the material - natural, artificial (including composites) and synthetic;

(c) purpose of the insulation - for hull structures, power plants, systems, etc.;

(d) principal method of application - loose, packed, smeared, spray-coated, installed in the form of sheets, board, blocks, mats, films, shells, wound, etc.; /196

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

(e) density* (ρ) in the structure: low ($\rho < 100\ kg/m^3$), medium (ρ 100–300 kg/m^3), and high ($\rho > 300\ kg/m^3$);

(f) physical state - powdered, granular, fibrous, composite (plasters, putties, spray-coated substances), sheets (roll fiberglass fabric), asbestos board, films (foil), pieces (lumps, shells, board , plates);

(g) conditions of use - cryogenic, low-temperature, medium-temperature, high-temperature, refractory;

(h) degree of combustibility (inflammability) in accordance with the Rules of the USSR Register - noncombustible (nonflammable),** respectively estimated in terms of the conventional inflammability coefficient $K \leqslant 0.1$, where K is determined by calorimetric methods and represents the ratio of the amount of heat evolved during the combustion of the sample under standardized conditions to the amount of heat in the igniting pulse; difficultly combustible** $0.5 > K > 0.1$; difficultly inflammable $2.1 > K > 0.5$; combustible** $K > 2.1$.

Values of K for various heat insulating materials are listed in Tables III.1 and III.2.

A large number of works[2,9,11] are devoted to the description of the properties, technology of production and application of heat-insulating materials, including those used on ships. We will confine ourselves to citing the essential properties of heat-insulating materials (Tables III.1 and III.2) and discuss the most typical and promising materials of only a few groups.

Such materials include foam materials (including foam plastics, foam glass and foam ceramics); lightweight mineral materials based on vermiculite; board (plate) and roll composite materials containing mineral or organic binders; special types of insulation, for example powder-vacuum or multilayer-vacuum insulation, and some others.

2. Foam Materials

Foam materials is the general designation of a large group of synthetic or artificial materials characterized by a unique cellular structure: the material has many closed or open pores filled with gas or air, and therefore has a low density and a low thermal conductivity.

Individual heat-insulating materials have been briefly described previously (Vol. I of the handbook, New Materials for Shipbuilding, Sudostroyeniye, 1966, p. 488; Vol. III, 1972, p. 101) and are discussed below in § 12 and section III.5. Here we are discussing only foam plastics possessing heat-insulating properties.

Depending on the nature of the starting materials, the foams used as heat insulators are subdivided into foam plastics (base - synthetic polymeric resins), foam glass (base - silicate glasses) and foam ceramics (base - ceramic compositions). /197

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*This classification is arbitrary.

**Terms adopted by the Rules of the USSR Register.

Table III.1

Heat-insulating materials for insulating the power plants of ship systems, heat exchangers and other equipment

No.	Material and standard	Bulk density, kg/m³		Thermal conductivity coefficient of material in insulation, kcal/m h°C	Inflammability characteristic of the material		Temperature of use of the material, °C (no higher than or in the range of)	Hygroscopicity of the material, %/h (not more than)		Bending strength, kg/cm² (not lower than)
		of material	of material and insulation		κ	e, %		by volume	by weight	
1	Chrysolite asbestos, grade 4-7, GOST 12871-67	400–700		0,092+0,00016t_{av}	<0,10	0,10	500	—	—	
2	Asbosurite	600	700	0,14+0,00015t_{av}	<0,10	0,60	900	—	—	—
3	Heat insulating asbestos paper, GOST 2630-67	Weight of 1 m² 0,85—1,85 kg/m² (depending on thickness)		0,135+0,00016t_{av}	0,04	4,00	500	—	—	—
4	Wool of kaolin composition, TU 1-11-245-72	80	250—600 (in the mat)	0,041+0,00014t_{av} (in the mat)	<0,10	0,10	From −60 to +1100	—	—	
5	Expanded vermiculite (GOST 12865-67):									
	Brand 100	100	110	0,049+0,00025t_{av}	<0,10	0,40	From −260 to +900	—	—	—
	» 150	150	170	0,054+0,00025t_{av}						
	» 200	200	230	0,059+0,00025t_{av}						
6	Technical grade coarse-haired felt for insulation, GOST 6418-67	160	170	0,045+0,00017t_{av}	0,78	30	From −60 to +100	$\frac{1,6}{24}$	$\frac{10}{24}$	
7	Heat insulating articles of brands FOV, FOP, FOVP (MRTU 5-967-11332—66):									
	Brand 230 » 250 » 280	230 250 280	230 250 280	0,07+0,00020t_{av}	0,07	2,50	600	$\frac{1,2}{24}$	$\frac{5}{24}$	1,7
8	Heat insulating lime-silica articles, MRTU 34-4601-68	225	225	0,052+0,00010t_{av}	0,10	3,00	600	$\frac{2,4}{120}$	$\frac{12}{120}$	3,5
9	Perlite articles with ceramic binder (MRTU 21-3-64):									
	Brand 250	250	250	0,056+0,00015t_{av}	0,04	0,60	900	$\frac{1,0}{120}$	$\frac{3,6}{120}$	4,0
	» 300	300	300	0,066+0,00015t_{av}						
10	Sovelite articles GOST 6788-62):									
	Brand 350	350	350	0,068+0,00016t_{av}	<0,10	...	400	—	—	1,7
	» 400	400	400	0,072+0,00016t_{av}						2,0
11	Asbestos cardboard, GOST 2850-58	1000—1300	1000—1300	0,135+0,00016t_{av}	<0,10	0,10	600	—	—	—
12	Technical grade cork granules	125 60—200	135 (in the charge)	0,040	4,20	65	От −180 до +100	$\frac{1,6}{24}$	$\frac{12}{24}$	—
13	Magnesia nouvel, MRTU 6-02-520-69	200	350	0,069+0,000083t_{av}	<0,10	0,20	330	—	—	—

Table III.1 continued

No.	Material and standard	Bulk density, kg/m^3		Thermal conductivity coefficient of material in insulation, kcal/m h°C	Inflammability characteristic of the material		Temperature of use of the material, °C (no higher than or in the range of)	Hygroscopicity of the material, %h (not more than)		Bending strength, kg/cm^2 (not lower than)
		of material	of material and insulation		K	φ, %		by Volume	by weight	
14	Heat insulating material of brand ATIMS: ATIMS-5 ATIMS-10 ATIMS-15	85 80 75	170 160 150	$0,034+0,00034t_{av}$	0,08	0,70	From −60 to +450	$\frac{0,2}{120}$	$\frac{2,0}{120}$	–
15	Heat insulating material of brand ATIMSS: ATIMSS-15 ATIMSS-20 ATIMSS-25 ATIMSS-30 ATIMSS-50	25	60	$0,03+0,00034t_{av}$	0,09	1,30	From −60 to +60	$\frac{0,1}{120}$	$\frac{3}{120}$	—
16	Heat insulating material of brand ATM-3: ATM-3-5; ATM-3-10; ATM-3-15; ATM-3-20	40	100	$0,034+0,00034t_{av}$	<0,10	—	From −60 to +450	$\frac{0,8}{720}$	$\frac{20}{720}$	—
17	Heat insulating material of brand VT4: VT4-5 VT4-10 VT4-15	50—60	100—120	0,045	>2,10	100	From −60 to +100	$\frac{0,6}{120}$	$\frac{10}{120}$	—
18	Heat insulating material of brand VT4S: VT4S-15 VT4S-20 VT4S-25 VT4S-30	25	60	0,45	>2,10	100	From −60 to +60	$\frac{0,2}{24}$	$\frac{9}{24}$	—
19	Cork in plates	240	240	0,050	4,00	62	From −50 to +100	$\frac{2,9}{24}$	$\frac{12}{24}$	2,5
20	Expansite plates	180 and 220 220	180 and 220 220	0,050	5,10	66	From −50 to +100	$\frac{1,8}{24}$	$\frac{10}{24}$	1,5
21	Heat insulating plates of PSB-S polystyrene foam plastic (GOST 15588-70): 25 30 40	25 30 40	25 30 40	0,045	Inflammable, self extinguishing	100	From −60 to +60	$\frac{0,16}{24}$	$\frac{4}{24}$	0,1 1,3 1,8
22	Sovelite powder	220	420 (in insulation) 440 (in plaster)	$0,0376+0,000162$	<0,10	0,20	400	—	—	—

Table III.1 continued

No.	Material and standard	Bulk density kg/m³		Thermal conductivity coefficient of material in insulation, kcal/m h°C	Inflammability characteristic of the material		Temperature of use of the material, °C (no higher than or in the range of)	Hygroscopicity of the material, %h (not more than)		Bending strength, kg/cm² (not lower than)
		of material	of material and insulation		K	σ, %		by volume	by weight	
23	Mat insulating plates FS-7, MRTU 6-05-958-65	120	120	0,050	0,58	6	From −55 to +40	$\frac{0{,}3}{24}$	$\frac{2{,}8}{24}$	6,0 With paper 4,0 Without paper
		100	100							4,0 With paper 2,5 Without paper
24	Mat insulating plates of FF foam plastic, MRTU 6-05-1302-70	120—140 150—190 190—230	120—140 150—190 190—230	0,055	0,56	4,4	From −60 to +100	$\frac{0{,}2}{120}$	$\frac{1}{120}$	6 8 10
25	Asbestos fabrics (GOST 6102-67):									
	AT-1 (1,4—1,7 mm) *	0,9—1,1	0,9—1,1	$0{,}106 + 0{,}00016t_{av}$	—	—	280	—	—	—
	AT-3 (2,0—2,9 mm)	1,2—1,5	1,2—1,5		0,30	6,50	250	—	—	—
	AT-7 (2,2—2,5 mm)	1,45—1,6	1,45—1,6		0,07	3—4	450	—	—	—
	AT-4 (2,6—3,5 mm)	1,4—1,84	1,4—1,85		0,81	6—11	250	—	—	—
	AT-8 (3,0—3,5 mm)	2,0—2,2	2,0—2,2		0,26	4,50	450	—	—	—
	AT-9 (1,9—2,0 mm)	1,05—1,2	1,05—1,2		—	—	450	—	—	—
	AT-11 (2,6—3,6 mm)	1,4—1,85	1,4—1,85				450	—	—	—
	AST-1 (1,4—2,1 mm) with a glass content not below 8% in the fabric	0,9—1,2	0,9—1,2		<0,10	0,15	500	—		
26	Roll aluminum foil for technical purposes, GOST 618-62	2700	9—10	$0{,}061 + 0{,}00022t_{av}$	<0,10	—	500	—	—	—
27	Asbestos cord, GOST 1779-72; diameter, mm:	Weight of 1 lin. m (for p. 27), kg/m								
	16	0,175	—	$0{,}12 + 0{,}00020t_{av}$	<0,10	0,80	400	—	—	—
	19	0,260	—							
	22	0,290	—							
	25	0,380								
28	Asbomagnesian cord, GOST 1779-72; diameter, mm:	Weight of 1 lin. m (for p. 28), kg/m								
	19	0,190	—	$0{,}095 + 0{,}00025t_{av}$	<0,10	0,85	400	—	—	—
	22	0,215	—							
	25	0,290	—							
	28	0,420	—							
	32	0,440								
29	"Asbopukhshanur ("Asbofluff cord") GOST 1779-72; diameter mm:									
	20	0,180	—	$0{,}1 + 0{,}00007t_{av}$	0,156	2,0	220 and 400	—	—	—
	25	0,120	—							
	30	0,380	—							

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* Column 1 indicates the thickness in parentheses.

Table III.2

Heat-insulating materials for insulating hull structures

No.	Material and standard	Density, kg/m³		Thermal conductivity coefficient at 20°C, kcal/m h °C		Inflammability characteristics of the material		Temperature of use, °C (no higher than)	Hygroscopicity, %/h, no higher than		Bending strength, kg/cm² (no lower than)
		of material	of material in insulation	of material (no higher than)	of insulation material (calculated)	K	a, %		by volume	by weight	
1	Asbokapron spray-coated heat insulation	—	180—200	—	0,065	<0.10	0,40	100	$\frac{1,2}{24}$	$\frac{6}{24}$	1,3
2	Asbocement spray-coated fireproof insulation	—	300—400	—	0,090	Same	0,60	950	$\frac{2}{24}$	$\frac{5}{24}$	2,5
3	Foam glass blocks for construction	150—250	150—250	0.060	0.100	» »	0,25	150	$\frac{0}{24}$	$\frac{0}{24}$	7,0
4	Technical grade coarse-haired felt (for insulation), GOST 6418-67	160	170	0.045	0.045	0.78	30	100	$\frac{1.6}{24}$	$\frac{10}{24}$	—
5	Heat insulating articles of glass staple fiber (GOST 10499-67):										
	PTO-75	51—75	60—80	0.040	0.045	0.10	3.40	60 (for ships of MMF, MRKh and MRF 120)	$\frac{0.5}{120}$	$\frac{6}{120}$	—
	PT-75	51—75	60—80			0.281	3.00		$\frac{0.4}{120}$	$\frac{5}{120}$	
	PT-50	36—50	60—60								
6	Technical grade cork granules	125	600—900 (in mastic)	0.035	0.150—0.200	4.20	65	100	$\frac{1.6}{24}$	$\frac{12}{24}$	—
7	Heat insulating material of brand ATIMS:										
	ATIMS-5	85	100	0,037	0,045	0,80	0,70	450	$\frac{0,2}{120}$	$\frac{0,2}{120}$	—
	ATIMS-10	80	95								
	ATIMS-15	75	90								
8	Heat insulating material of brand ATIMSS:										
	ATIMSS-15	25	50	0,037	0,045	0,09	1,30	60	$\frac{0,1}{120}$	$\frac{3}{120}$	—
	ATIMSS-20										
	ATIMSS-25										
	ATIMSS-30										
	ATIMSS-50										
9	Heat insulating material of brand VT4:										
	VT4-5	50—60	60—70	0,035	0,045	>2.10	100	100	$\frac{0,6}{120}$	$\frac{10}{120}$	—
	VT4-10										
	VT4-15										
10	Heat insulating material of brand VT4S:										
	VT4S-15	25	60	0.035	0,045	>2.10	100	60	$\frac{0,2}{24}$	$\frac{9}{24}$	—
	VT4S-20										
	VT4S-25										
	VT4S-30										

Table III.2 continued

No.	Material and standard	Density, kg/m³		Thermal conductivity coefficient at 20°C, kcal/m h°C		Inflammability characteristic of the material		Temperature of use °C (no higher than)	Hygroscopicity, %h no higher than		Bending strength, kg/cm² (no lower than)
		of material	of material in insulation	of material (no higher than)	of insulation material (calculated)	K	a, %		by Volume	by Weight	
11	Minerallike plates with synthetic binder (GOST 9573—72):										
	PM	100	125	0,045	0,055	<0,10	About 1,0	300	$\frac{0,3}{120}$	$\frac{2}{120}$	—
	PP	150	180								
	PZh	175	200								
	PPM-40	40	50								
	PPM-50	50	65								
	PPM-80	80	80								
	PPM-100	100	100								
12	PKhV plate foam plastic (MRTU 6-05-1179—69):										
	PKhV -1-85	85	85	0,045	0,050	1,63	80,0	60	$\frac{0,3}{120}$	$\frac{2,5}{120}$	10—15
	PKhV -1-115	115	115								
	PKhV -2-150	150	150			1,75	18—20	26	$\frac{0,4}{120}$	$\frac{2,5}{120}$	10—15
	PKhV -2-195	195	195								
13	Polyurethane foam plastic of brand PPU-3N	50—80	50—80	0,035	0,040	2,36	54	70	$\frac{0,27}{24}$	$\frac{3,4}{24}$	5,0
14	Polyurethane foam plastic of brand PPU-304N	30—50	30—50	0,030	0.035	0,83	30	80	$\frac{0,18}{24}$	3,6	2,0
15	Heat insulating plates of PSB-S polystyrene foam plastic (GOST 15588—70):										
	25	25	25	0,035	0,045	Inflammable, self-extinguishing	100	60	$\frac{0,2}{24}$	$\frac{4}{24}$	1,0
	30	30	30								1,3
	40	40	40								1,8
16	Cork in plates	240	240	0,045	0,050	4,00	62	100	$\frac{2,9}{24}$	$\frac{12}{24}$	2,5
17	Expansite plates	180	180	0,045	0,050	5,10	66	100	$\frac{1,8}{24}$	$\frac{10}{24}$	1,5
		220	220	0,045	0,050	—	—	—	—	—	1,0
		220	220	0,045	0,050	—	—	—	$\frac{1,9}{24}$	$\frac{8,5}{24}$	1,5
18	Heat insulating plates of brand FS-7$_2$, MRTU 6-06-958—65	70	70	0,045	0,050	0,58	6	40	$\frac{0,3}{24}$	$\frac{2,8}{24}$	3,0 (with paper) 2,0 (without paper) 4,0 (with paper) 2,5 (without paper)
		100	100								
19	Heat insulating plates of FF foam plastic	120—140 150—190 190—230	120—120 150—190 190—230	0,045	0,055	0,56	4,4	100	$\frac{0,2}{120}$	$\frac{1}{120}$	6 8
20	Roll aluminum foil for technical purposes, GOST 618-62	2700	6—9	—	0,050	<0,10	—	500	—	—	—

The common properties of these materials, despite their completely different nature, are a low density ($\rho = 20-60$ kg/m^3), low thermal conductivity ($\lambda = 0.03-0.05$ kcal/m h °C), and the fact that it is possible to vary their various properties widely, which makes it possible to select the optimum variants for a specific area of application.

Foam plastic heat insulation may be made in two variants: by installing sheets or blocks of foam plastic, then sewing or pasting decorative material around it, or by spraying *foaming* compositions forming the foam plastic on the spot. Such for example is the rigid foam polyurethane of type HartMoltopren, widely employed in foreign shipbuilding for heat insulation of ships.

For standard $\rho = 30$ kg/m^3, its $\sigma_u = 3.5$ kg/cm^2, $\sigma_c = 1.8$ kg/cm^2, $a_1 = 0.6$ kg cm/cm^2; the material has 95% of closed pores. The hygroscopicity is 1-3%; $\lambda = 0.020-0.022$ kcal/(m h °C).

Figure III.1 shows comparative characteristics of the basic properties of certain foam plastics: λ vs ρ (a); λ vs t (b); σ_u vs ρ (c); σ_c vsρ (d); σ_{sh} vs ρ (e); E vs ρ (f); σ_c vs t (g); E_{sh} vs t (h).

Figure III.2 shows the basic characteristics of the properties of a two-layer construction material - foam polyurethane blocks with glass-reinforced plastic linings (sandwich structure).

A similar group of graphs in Fig. III.3 shows data on materials for fireproof heat insulation made in the form of foam plastic sheets 30-120 mm thick lined on both sides with sheet asbestos ($\delta = 1$ mm).

The foam plastic core of this material consists of a composition of foam polystyrene (90%) and silicon-containing filler (10%).

In the case of a fire, in which the temperature rises to 800-1000°C, the foam plastic burns off, while the silicate skeleton remains. In this material, $\lambda = 0.039$ kcal/(m h °C), $\sigma_c = 3-4$ kg/cm^2, $\sigma_{shear} = 14-15$ kg/cm^2, $\rho = 160$ kg/m^3.

Polyurethane foam plastics (see Vol. III of this handbook, 1972, Sudostroyeniye Publishing House, p. 131) are very promising shipbuilding heat-insulating materials possessing a combination of valuable properties (low ρ and λ values, fairly high σ_u, σ_c, σ_{bend} values), and also because of their technological workability. These materials may be used as preformed and foamed products (sheets, blocks, individual articles), and also as sprayed compositions which foam when applied on the surface to be protected, as well as filling compositions foaming in the cavities and volumes which they occupy.

A similar technological latitude has served as the basis for using polyurethane /200
foam plastics not only as heat-insulating materials but simultaneously to lighten the structures and also to fill not easily accessible cavities in order to provide protection from corrosion, sound insulation, mechanical bracing of parts, etc.

When pouring *polyurethane foaming compositions*, (for example, when filling buoyancy volumes, rudder blade cavities, fairings, hull structures), use is also /202
made of special machines and devices which mechanize these operations.

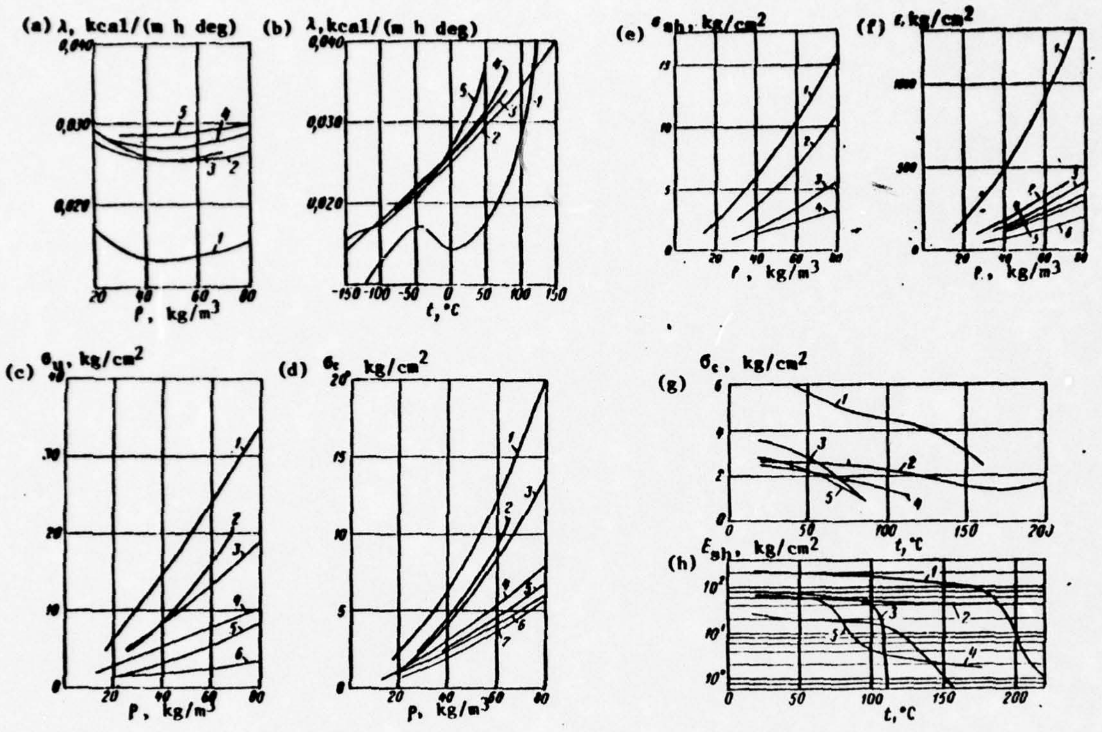

Fig. III.1. Comparative characteristics of the properties of certain foam plastics

a - thermal conductivity λ vs density ρ.
1 - foam polyurethane PPU (R11 blowing agent); 2 - phenol foam plastic FPP; 3 - *polymethacrylamide* PM-1;
4 - foam polystyrene (mold blown) PPS; 5 - foam polyurethane (CO_2 blowing agent);
b - thermal conductivity λ vs temperature.
1 - PPU $\rho = 40$ kg/m³, R11 blowing agent; 2 - PM-1 $\rho = 35$ kg/m³; 3 - PPS $\rho = 40$ kg/m³ (mold blown); 4 - FPP $\rho = 40$ kg/m³; 5 - foam polyvinylchloride (PPKhV) $\rho = 50$ kg/m³;
c - tensile strength σ_u vs density ρ at 20°C.
1 - PM-1; 2 - PPS, extruded; 3 - PPKhV; 4 - PPS (mold blown); 5 - PPU; 6 - FPP;
d - compression resistance σ_c vs density ρ at 20°C.
1 - PM-1; 2 - PPS, extruded; 3 - PPKhV; 4 - PPS (mold blown); 5 - PPKhV; 6 - FPP; 7 - PPU;
e - shearing resistance vs density. 1 - PM-1; 2 - PPKhV; 3 - PPU; 4 - PPKhV;
f - Young's modulus vs density. 1 - PM-1; 2 - PPS (extruded); 3 - PPKhV; 4 - PPkhV; 5 - FPP; 6 - PPU;
g - σ_c for various foam plastics (with $\rho = 40$ kg/m³) vs temperature. 1 - PM-1; 2 - FPP; 3 - PPKhV; 4 - PPU; 5 - PPS (mold blown)
h - shear modulus for various foam plastics (with $\rho = 40$ kg/m³) vs temperature. 1 - PM-1; 2 - FPP; 3 - PPS (mold blown); 4 - PPKhV; 5 - PPU.

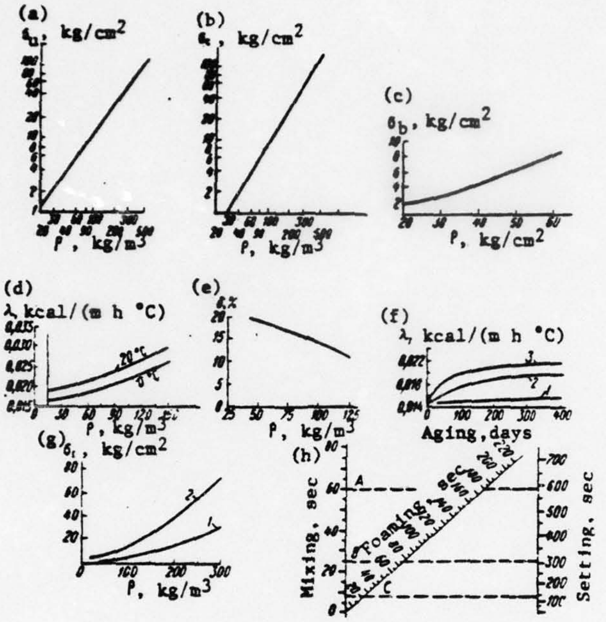

Fig. III.2. Some characteristics of two-layer foam polyurethane blocks:

a - foam polyurethane KK, σ_u vs ρ; b - polyurethane foam plastic σ_c vs ρ; c - σ_b vs ρ;

d - λ vs ρ; e - δ vs ρ; f - change in λ with aging foam plastic.

1 - sandwich with fiber glass linings; 2 - PPU (at 20°C); 3 - PPU (at 50°C);

g - σ_c vs ρ for PPU with open (1) and closed (2) cells;
h - nomogram relating the lengths of mixing (1), foaming (2) and setting (3) of foam polyurethane.

Dashed lines indicate examples of use (from the top down). A: mixing - 60, foaming - 180, setting - 580; B: mixing - 25, foaming - 75, setting - 310; C: mixing - 8, foaming - 25, setting - 150.

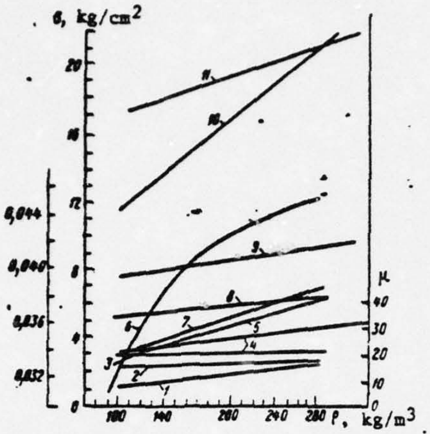

Fig. III.3. Some characteristics of foam plastic blocks lined with asbestos. Curves for brands IA and IIA: 1 - σ_u vs ρ; 2 - μ vs ρ; 3 - σ_{sh} vs ρ; 4 - σ_b vs ρ; 5 - σ_c vs ρ; 6 - λ vs ρ. Curves for brands I and II: 7 - σ_c vs ρ; 8 - σ_u vs ρ; 9 - μ vs ρ; 10 - σ_{sh} vs ρ; 11 - σ_b vs ρ.

Table II.3

Characteristics of rigid foam plastics

Properties*	Brands of foam plastic		
	31	51	71
ρ_{app}, kg/m³	30	50	70
σ_u, kg/cm²	10	19	29
σ_c, kg/cm²	4	9	15
σ_b, kg/cm²	9	19	30
σ_{sh}, kg/cm²	4	9	13
E_Y, kg/cm²	300	600	1000
E_{sh}, kg/cm²	130	250	400
a_i, kg cm/cm²	0,4	0,7	1,0
Heat resistance, °C	200	195	190
λ, kcal/(m h °C)	0,027	0.025	0,026
W_{50} days, %	18	14	14
$\varepsilon_{2.8}$ mHz	1,04	1,07	1,10
tan $\delta_{2.8}$ mHz x 10^4	6	8	10
ρ_s, Ohm	$2 \cdot 10^{13}$	$9 \cdot 10^{12}$	$5,5 \cdot 10^{12}$

*All properties at 23°C, φ = 50%.

Volume III of this handbook (1972, Sudostroyeniye Publishing House, p. 102) gives the properties of certain brands of foam polyurethane plastics which are of interest in shipbuilding.

Polymethacrylamide with an admixture of soluble gas-forming agent splitting off ammonia is used to obtain by foaming at 170-230°C rigid foam plastics suitable for heavy duty service.

Foam plastics of this type are resistant to vibration and wear, and they are mechanically stronger than all other rigid foam plastics of the same density; they are thermally stable and resistant to organic solvents. Some characteristics of Rohacell foam plastics are shown in Table III.3.

3. Vermiculite

Expanded vermiculite (thermovermiculite) is a granular heat-insulating material obtained by grinding and calcining the natural mineral vermiculite (hydrophlogopite) - a highly hydrated magnesium aluminosilicate of variable composition.

The limits of fluctuations in the content (percent) of the various components of vermiculite are: SiO_2 37-42 , MgO 14-28, Fe_2O_3 5-17, FeO 1-3, Al_2O_3 10-13, H_2O 8-20 (K_2O + Na_2O) 1-2.

On rapid heating, vermiculite splits into separate mica plates lightly bonded to each other, so that the grains expand considerably and bend partially [hence the name vermiculis (worm-shaped)].

On expanding, the increase in volume is tenfold, and the increase in grain thickness ranges from 15 to 40-fold.

Depending on the grain size, expanded vermiculite is divided into two fractions: fine (from 015-0.25 to 3 mm) and coarse (from 3 to 10-15 mm).

The bulk density without compaction ranges from 100 to 300 kg/m³ (Fig. III.4).

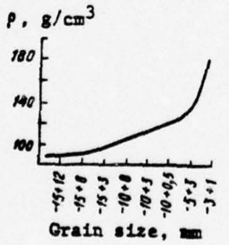

Fig. III.4. Density of vermiculite vs grain size

Table III.4

Some characteristics of expanded vermiculite and vermiculite articles

Material	ρ, kg/m^3	λ, kcal/(m h deg)	σ_c, kg/m^2	σ_b, kg/cm^2	Refractoriness, °C
Expanded vermiculite:					
of Potanyanskiy deposit (5-10 mm, 0.6-5.0 mm and 0.0-0.6 mm fractions);	up to 100	0.035-0.050	-	-	1270
of Kovdor deposit (5-10 mm, 0.6-5.0 mm and 0.0-0.6 mm fractions)	up to 150	0.06	-	-	1350
Commercial grades of expanded vermiculite (0.15-3 mm, and 3 to 10-15 mm fractions)	100-300	0.065-0.085	-	-	-
Unfired asbestos-vermiculite articles	250-350	<0.09	-	2-2.5	-
Vermiculite concretes	300-900	-	3-25	-	-
	500	0.09	5	-	-
Vermiculite-ceramic articles	350-450	0.07-0.08	4-15	2-3	>1350

Table III.5

Compositions of mixtures (in terms of dry substance) for preparing asbestos-vermiculite articles

Starting materials	Content of components, wt.%			
	I*	II	III	IV
Expanded vermiculite	67	59	56	56
Asbestos of grade V	18	7.5	17	17
Bentonite clay	10	-	-	-
Milled diatomaceous earth	-	7.5	-	-
Water glass	-	22.3	-	-
Sodium fluosilicate	-	3.7	-	-
Phenolic alcohol (resin)	-	-	12	15
Bituminous bentonite paste	-	-	-	12
Bituminous diatomaceous paste	-	-	15	-
Starch	5	-	-	-

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*Roman numerals denote composition numbers.

Expanded vermiculite (Table III.4) with additions of binders can be used for the preparation of two types of heat-insulating products:

(a) unfired ones - asbestos-vermiculite products (among the compositions shown in Table III.5, characterized by t_{work} up to 600°C) and vermiculite concretes of expanded vermiculite and cement of brand 600, taken in the proportion 1:1 - 1:2.5;

(b) fired or vermiculite-ceramic products (among mixtures of vermiculite /203
and refractory clay, taken in the weight proportion of 3:1 - 4:1), characterized by t_{work} up to 1100°C.

Composition of vermiculite concrete (in wt.%) /204

Portland cement 400	57
Expanded vermiculite of brand 125 (2.5-10 mm grain)	5.7
MB-40 asbestos	2.8
Water	34.5

This vermiculite concrete has $\rho = 1200$ kg/m^3, $\lambda = 0.18$–0.22 kcal/(m h deg) and $t_{work} = 850$–950°C, and serves as a sublayer for mastic deck coverings (of "Neva-3U" type) in cases where fireproof protection of deck coverings is required. The optimum thickness of a layer of vermiculite concrete on steel is 30-35 mm, and that of the "Neva-3U" mastic, 15-20 mm.

4. Expanded Perlite

Heat-insulating materials include expanded perlite (perlite sand - a volcanic rock containing water - fired in the suspended state in shaft furnaces).

Expanded perlite sand is mixed with different types of binders (mineral, organic) and shaped into articles used for heat insulation.

The characteristics of certain articles obtained from perlite are shown in Table III.6.

5. Board Heat-Insulating Materials

Heat-insulating materials used in structures in the form of finished board (plates, panels) and usually requiring no additional treatment (enclosing, painting, gluing, etc.) include articles formed under plant conditions from various compositions.

The most modern materials of this type are asbosilite (USSR), neptunite (GDR) and marinite (England).

The characteristics of these materials, which are used not only for heat insulation but also for fireproofing on ships, are discussed in more detail below (§ 11 and Table III.15).

Table III.6

Characteristics of certain heat insulating articles obtained from perlite

Article	Binder	ρ, kg/m³		λ, kcal/(m h °C)	Temperature up to which service is possible, °C
		of sand	of article		
Ceramic-perlite-phosphate	Refractory clay and phosphates	60—120	250—400	<0,2 (600°) *	1150
Ceramic perlite	Clay		250—400	0,06—0,09	900
Perlite, fired lightweight	Fusible clays	80	100—200	0,05—0,07 (20°)	600—700
PPKhV-1 plates	PKhV-resin	70—100	<160	0,055	100
Bitumen-perlite	Bitumen	60—120	300—450	0.07—0,09 (20°)	160
Cement-perlite	Cement		250—350	0,06—0,075 (25°) 0,11—0,12 (325° C)	600
Perlite-gel	Water glass and fluosilicate		200—250	0,051—0,056 (25°) 0,099—0,104 (325°)	
Phenolic perlite and phenolic ceramic perlite plates	Phenolic alcohols	—	—	—	—
Filter perlite powder	-	150—400		0,05—0,08	130

*Throughout this column, the temperature indicated in parentheses is in degrees Centigrade.

New varieties of fiber glass materials may be used for heat and sound insulation, in particular, articles made from them (plates, rolls) obtained by the so-called centrifugal blast method (CFB).

Fiber obtained by the CFB method (combined action of centrifugal forces and gas combustion products on the glass melt when the filament is pulled) has an increased strength, is more homogeneous, and makes it possible to obtain articles of better quality. By binding the CFB fiber with synthetic resins, one obtains a shaped composition which after the resin sets has a combination of valuable properties.

Plates containing fibers obtained by the CFB method, with a binder of a mixture of phenolic alcohols and alkyd resin VPF-45 in the proportion of 5:1, are made /206 with fiber having the following properties: density - for brand PT-75, 30-40 kg/m^3; for PT-50, 10 kg/m^3; mean diameter of fiber - less than 6 μm; content of nonfibrous inclusions, 0; loss on ignition, 12%; hygroscopicity for 5 days, 4%; recovery coefficient, 95%.

The CFB roll material has a density of 21.0 kg/m^3 under a load of 1 g/cm^2 and 29.0 kg/m^3 under a load of 5 g/cm^2.

6. Heat Insulation of Cryogenic Devices

For purposes of cryogenic engineering, which requires careful protection of the apparatus, containers and connecting lines from the influx of heat, ordinary

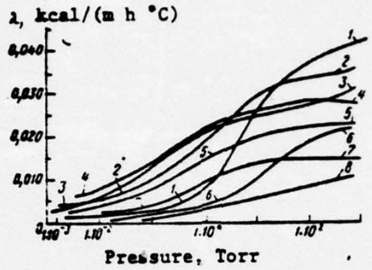

Fig. III.5. Apparent average thermal conductivity of certain types of Soviet-made vacuum-powder heat insulating materials in the 790-78 K temperature range (layer thickness, 9-72 mm)

1 - magnesia; 2 - mineral wool; 3 - perlite; 4 - coarse-fiber glass wool (18-20 μm); 5 - fine-fiber glass wool (4-7 μm); 6 - silica gel; 7 - Mipor; 8 - silicoaerogel.

heat insulation is inadequate. In such cases, special types of heat insulation are used, mainly high-vacuum, powder-vacuum and multilayer-vacuum types.

High-vacuum insulation is obtained by structural methods: creating a high vacuum ($1 \cdot 10^{-5}$-$1 \cdot 10^{-6}$ Torr) in the heat-insulating space and setting up in this space free-standing or cooled shields which sharply decrease the radiant heat influx. For example, high-vacuum insulation with shields cooled by liquid nitrogen is uniquely suited for the storage and transportation of liquid helium, for which ordinary Dewar flasks are unsuitable.

Powder-vacuum insulation consists in filling the insulation space with various powdered materials and reducing the pressure to 10^{-1}-10^{-2} Torr in this space.

As shown in Fig. III.5, the thermal conductivity of all powdered heat-insulating materials drops sharply, since the transfer of heat by the gas usually present in the pores of insulation materials is eliminated. /207

Figure III.5 shows comparative values of the thermal conductivity of some types of Soviet-made materials used in the form of vacuum-powder insulation for cryogenic devices.

Materials used for powder-vacuum insulation include: aerogel, perlite, silica gel, Mipor, and fiber glass, to which is frequently added aluminum or copper dust (40-60% of its mass), which shields the material and lowers the radiant heat transfer, thus reducing the thermal conductivity coefficient by a factor of 3-4.

Multilayered vacuum heat insulation is formed by alternating layers of materials with a high reflectivity and low thermal conductivity, for example aluminum foil and fiber glass fabric. When the residual pressure in the heat-insulating space is $1 \cdot 10^{-3}$-$1 \cdot 10^{-4}$ Torr, the heat transport by the gas is sharply reduced, and the nominal thermal conductivity of the layers becomes approximately 1/10 that of the vacuum-powder materials and approximately 1/100 that of bulk heat insulation.

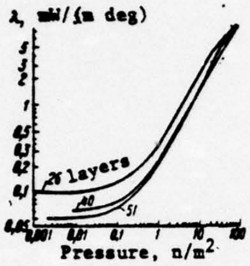

Fig. III.6. Thermal conductivity of multilayered insulation vs pressure (T = 293-90 K)

Numbers on curves denote the number of layers of multilayer insulation.

The optimum number of insulation layers is 20-30 per cm of thickness. The chief area of application of this insulation are pipes and cryogenic vessels.

Figure III.6 shows the thermal conductivity of multilayer insulation (aluminum foil - fiber glass fabric) vs pressure (T = 293-90 K) for different numbers of layers n = 26, 40, 51.

III.2. ASBESTOS AND ASBESTOS MATERIALS

7. Asbestos. General Properties

The name "asbestos" includes a group of fibrous varieties of certain minerals. According to their mineralogical origin, two main asbestos groups are distinguished:

amphiboles $[X_{2-3}Y_5Z_8O_{22}(OH, F, Cl)_2]$, where X - Na, Ca, K, Li; Y - Mg, Fe, Mn; Z - Si, Al, Ti, and

serpentines $Mg_6[Si_4O_{10}](OH)_4$.

A common property of these minerals is the filament shape of the crystals and their ability to be split into the finest fibers possessing a high mechanical strength and elasticity. The tensile strength weight ratio of asbestos fibers is much higher than that of many construction metals. In addition, asbestoses are characterized by a high thermal and atmospheric stability and chemical resistance. Compositions of the chief varieties of asbestos are shown in Table III.7.

The two main varieties which have been applied in industry are chrysotile asbestos (GOST 12871-67) and anthophyllite asbestos (STU 49-161-62 MPSM).

Anthophyllite asbestos is characterized by a low strength, different fiber lengths and a high acid resistance. It is mainly used as a filler in the production of oxygen-resistant plastics, asbestos board, etc. It is manufactured in two grades differing in fiber length. /208

Table III.7

Chemical composition of main types of asbestos

Principal mineral	Theoretical formula	Main components										Loss on ignition	Tensile strength of fibers, kg/mm²
		SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	K_2O	Na_2O	H_2O		
		Content, wt.%											
Crocidolite (riebeckite)	$Na_2Fe_3^{2+}Fe_2^{3+}[Si_8O_{22}](OH)_2$	50 52	0,2	18,5—22	17—19,5	—	1,5	0,2	—	6	3	—	330
Rhodusite	$Na_2(Mg,Fe^{2+})_3Fe_2^{3+}[Si_8O_{22}]\times$ $\times(OH,F)_2$	54	1,5	14,5	7	—	10,5	1,5	5	0,5	1,5	2,5	170
Magnesia-arfvedsonite	$Na_3(Fe^{2+}Mg)_4(Fe^{3+},Al)\times$ $\times[Si_8O_{22}](OH,F)_2$	56	0,3	10,5	2	—	17,5	1,3	1,8	7,9	3,2	—	344
Richterite	$CaNa_2Mg_5[Si_8O_{22}](OH)_2$	55,5	—	4,5	2,3	—	20	9	1,5	4,8	0,8	0,5	—
Actinolite	$Ca_2(Mg,Fe^{2+})_5[Si_8O_{22}](OH)_2$	55,6	2,5	2,6	6,7	1,7	18,5	8,4	0,5	—	—	3,1	—
Tremolite	$Ca_2Mg_5[Si_8O_{22}](OH)_2$	56—60	0,3	—	1,4	0,2	25,2	12,7	—	—	1,5	—	—
Cummingtonite	$(Fe^{2+}Mg)_7[Si_8O_{22}](OH)_2$	49	—	7,2	33,5	—	5,4	0,8	0,1	0,8	—	2,5	308
Amosite	$5MgO\cdot18FeO\cdot26SiO_2\cdot5H_2O$	46—50	0,8	3,7	35—40	—	5,9	1,1	—	—	2,9	—	—
Anthophyllite	$(Mg,Fe^{2+})_7[Si_8O_{22}](OH)_2$	49—50	0,5—1,3	0,1—0,3	5—6,5	0,08—0,1	30	0,5—1,0	—	—	10	2,7	155
Chrysotile	$Mg_3[Si_2O_5](OH)_4$	39—43	0,6—2,2	0,2—1,1	0,3—2,2	0,06—0,09	39—43	0,1—1	—	0,1	12—16	—	250—300

* The values are only tentative, since they refer to specific asbestos samples. Appreciable fluctuations of these values are possible for each type.

Crocidolite (blue) and amosite asbestos is also applied in industry to an appreciable extent. Some properties of asbestos fibers are also listed in Table III.7.

Chrysotile asbestos can be split into fine, flexible, elastic fibers of high strength suitable for the production of textile materials. The long-time heat resistance is 550°C, and the short-time heat resistance is 700°C. Chrysotile asbestos is highly stable to the action of alkali but insufficiently acid resistant. According to the fiber length and dust content, it is subdivided into 9 grades (from 0 to 8) and according to the texture, into three groups: rigid, semirigid and soft.

In addition, seven brands denoting the asbestos grade and fiber size have been established, along with the following additional symbols:

AK - lumpy, long-fibered, rigid-textured;

DV - long-fibered, rigid-textured; /209

Zh - rigid-textured;

PRZh - intermediate brands between rigid and semirigid textures;

P - semirigid-textured;

M - soft-textured;

K - chambered, soft-textured.

Asbestos brands AK, DV-0-80, DV-0-55, Zh-1-50, Zh-1-38, Zh-2-20, Zh-3-40, PRZh-2-30, PRZh-2-15, P-2-30, and P-2-15 are designed mainly for the production of textile articles. Asbestos of brands P and M (grades 3, 4 and 5) as well as brands P-6-40 and M-6-40 is used for producing asbestos cement articles. Brands K-6-30 and K-6-20 are used for heat insluation in the production of plastics. Asbestos of brand K-6-5 is used in the production of asbestos-pitch tiles.

8. Asbestos Materials

Chrysotile asbestos is used as the base of important technical materials: asbestos thread or yarn and articles made with it (cord, fabric, board, paper, jointing, etc.).

Table III.8 lists the basic properties of certain asbestos materials. /212

Asbestos and materials obtained with it as the base have various applications in technology. They are used as:

(1) fireproofing and electrical, thermal and acoustic insulating materials;

(2) sealing materials;

(3) active and reinforcing fillers in plastics, adhesives, rubbers, asbestos cement and various composite materials;

Table III.8

Basic properties of asbestos fabrics

Brand	Weave type	Thread thickness in the texture ±10% (metric number)		Fabric composition, %		Width, mm	Mass, g/m^2	Thickness mm	Number of threads per 100mm		Breaking load of 50x100 mm strip, not less than		Mass loss on ignition, %, not more than	Maximum permissible service temperature, °C
		Warp	Weft	Asbestos. not less than	Binding fiber, not more than				Warp	Weft	Warp	Weft		
AT-1	Linen	340×2 (3,0/2)	340×2 (3,0/2)	84,5	15,5 (cotton)	1040±20 1350±20 1550±20	900—1100	1,40—1,70	80±2	42±2	65	27	29,0	400
AT-2	»	500×2 (2,0/2)	500×2 (2,0/2)	81,5	18,5 (cotton)	1040±20 1350±20 1550±20	950—1150	1,40—1,90	60±2	30±2	50	17	32,0	400
AT-3	»	500×3 (2,0/3)	500×3 (2,0/3)	81,5	18,5 (cotton)	1040±20 1350±20 1550±20	1200—1500	2,00—2,90	45±2	23±2	50	20	32,0	400
AT-4	»	840×2 (1,2/2)	840×2 (1,2/2)	81,5	18,5 (cotton)	1040±20 1350±20 1550±20	1400—1850	2,60—3,50	45±2	19±2	44	14	32,0	400
AT-5 (with brass wire)	Rep	(500×3)+1 (2,0/3+1)	(500×3)+1 (2,0/3+1)	81,5	18,5 (cotton)	1040±20 1550±20	1300—1600	1,80—2,50	45±2	19±2	38	25	32,0	400
AT-6	Serge	520×2 (1,9/2)	520×3 (1,9/3)	95,0	5,0 (cotton)	1550±20	3000—3400	3,40—3,80	138±2	74±2	265	150	19,0	500
AT-7	Linen	460×2 (2,2/2)	460×3 (2,2/3)	90,0	10,0 (cotton)	1520±20	1450—1600	2,20—2,50	82±2	42±2	85	60	23,5	450
AT-8	Serge	460×2 (2,2/2)	460×4 (2,2/4)	90,0	10,0 (cotton)	1500±20	2000—2200	3,00—3,50	72±2	66±2	80	100	23,5	450
AT-9	Linen	460×2 (2,2/2)	460×3 (2,2/3)	90,0	10,0 (cotton)	1500±20	1050—1200	1,90—2,00	58±2	30±2	70	30	23,5	450
AT-10	Rep	165×2 (6,0/2)	165×2 (6,0/2)	83.5	16,5 (cotton)	1000±20 1200±20 1550±20	800—900	1,10—1,30	150±2	58±2	90	30	32	400
AT-11	Linen	840×2 (1,2/2)	840×2 (1,2/2)	90,0	10,0 (cotton)	1040±20 1350±20 1550±20	1400—1850	2,60—3,50	45±2	19±2	44	14	23,5	450
AST-1	»	(340×2)+ +HC (13,0×6) (3,0/2+HC75/6)	(340×2)+ +HC (13,0×6) (3,0/2+HC75/6)	78,5	13,5 (cotton) 8,0 (glass not less than)	1040±20 1550±20	900—1200	1,40—2,10	80±2	32±2	100	40	27	500
ALT-1	Rep	165×2 (6,0/2)	165×2 (6,0/2)	83,5	16,5 (dacron)	1000±20 1200±20 1550±20	800—900	1,10—1,30	150±2	60±2	100	40	32	500
ALT-2	Linen	280×2 (3,5/2)	280×2 (3,5/2)	50,0	50,0 (dacron)	1000±20 1200±20 1550±20	500—600	1,20—1,50	44±2	30±2	84	68	00,0	300

(4) filtering and absorbing materials.

Asbestos fabrics (AT-1 - AT-5 GOST 6102-67) are used mainly for heat insulation (see Table III.8).

New materials obtained with asbestos as the base include fabric or paper composites from asbestos and fiber glass with resin binders: asbestos-ceramic compositions of asbestos and ceramic fibers; metallized asbestos fibers and fabrics; fabrics made of metal wire and asbestos fibers; asbestos-graphite compositions made of graphite powders, asbestos fibers and resin binder; pastes of asbestos, zircon and silicon with resin binders; asbestos fluorineplastics; asbestos polyamides and many others. In many compositions, asbestos functions as a heat-resistant reinforcing component.

The properties of certain composities are listed in Table III.9.

Table III.9

Properties of certain asbestos compositions

Property	Composition No.			
	1* (asbestos-polyamide-phenol composition)	2 (asbestos-glass paper with epoxy binder)	3 (laminated asbestos phenolic)	4 (asbestos felt with phenol binder)
ρ, g/cm^3	1.36-1.4	1.7	1.8	1.75
σ_u, kg/mm^2;				
in longitudinal bending	11.9	70.91	35-38	-
in transverse bending	9.8	-	-	-
in longitudinal extension	9.8	70-84	32-38	20
in transverse extension	6.3	-	-	-
σ_c	21	35-42	-	13-16
E$\cdot$10^{-2}, kg/mm^2:				
in longitudinal extension	9.6	28-35	35-42	-
in transverse extension	7.4	-	-	-
in bending	-	25-28	35-42	-
in compression	-	26-31	-	-

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*Thermal conductivity of composition No. 1: λ = 0.08-0.09 kcal/(m h °C); heat capacity of composition No. 1: c - 0.29 kcal/g °C.

9. Spray-Coated Asbestos Insulation /213

Asbestos is the basic component of many heat-insulating and fireproofing compositions applied on the surface by mechanized methods, mainly spray coating. Such compositions include the asbestos cement and asbestos capron compositions.

The asbestos-cement mixture spray coated on surfaces is designed for insulation and consists of asbestos of grade P-III-50 or P-IV-20 (GOST 12871-67) and portland cement of grade not below 500 (GOST 10178-62) or fast-setting or plasticized cement (GOST 10178-62).

The weight ratio of asbestos (fluffy) and cement (dry) is 2:1. The dry mixture is fed into a spray gun together with water (1:1) and is sprayed with compressed air and in the form of a semiliquid mass onto the surface to be protected in a layer of necessary thickness (usually 15-20 mm).

The spray-coated asbestos capron heat insulation is obtained by mixing 93 wt.% of fluffy asbestos of grades P-III-50 or P-IV-20 (GOST 12871-67) with 7% of capron noil (fiber length, 10-15 mm), the binder being a solution of potassium silicate ($M = 2.9$-3.2; $\rho = 1.41$-1.45 g/cm^3) diluted with fresh water to $\rho = 1.25$-1.26 g/cm^3. The mixture is atomized at an air pressure of 2.5 kg/cm^2. The approximate ratio of the dry mixture to the solution is 1:1.

Prior to the spraying of both the asbestos-cement and asbestos-capron mixture, to improve the adhesion, the surface is coated with a cement-latex primer of the following composition:

Latex DVKhB-70 grade A (GOST 9501-60)	37
Stabilizer K (acid casein 14%; calcined soda 1%; water 85%)	11
Portland cement of grade not below 400 (GOST 10178-62)	52

The adhesive strength of the spray-coated insulation increases if wire pins 6-8 mm long are first welded to the surface being treated at a distance of 250-300 mm from each other (at the corners of squares), and after the insulation is applied, the ends of the pins are bent at a distance of 1/3 of the specified thickness. /214

The properties of the insulation obtained after drying are given in Table III.10.

Table III.10

Some characteristics of spray-coated insulation masses

Type of mass	ρ, kg/m^3	λ, kcal/(m h °C)	Ultimate strength, kg/cm^2			W_{24}, %	Heat resistance 1 h, °C
			σ_u (layer separation)	σ_b	σ_c (without deformation)		
Asbestos cement	300-400	0.09-0.095	0.5	2-2.5	>0.5	up to 5	950
Asbestos capron	180-250	0.06	0.05	1.3	-	up to 6	-

III.3. HEAT-SHIELDING MATERIALS

During the operation of many modern machines and installations, individual parts or components may be subjected to intense heat fluxes at temperatures equal to or exceeding the melting point or decomposition temperature of the materials of which they are made.

To insure the efficient operation of such parts (if they cannot be made of materials possessing a sufficiently high heat resistance), it is necessary to resort to various methods of protecting them from heat. Of the many possible heat-shielding variants, the following three may be considered the main ones:

(1) supplying a cooling liquid or gas to the wall opposite the heated side or to the permeable volume (pores, channels) of the material being heated;

(2) applying on the heated surface refractory coatings or linings capable of preserving their state of aggregation for a long time and possessing a low thermal conductivity;

(3) applying on the heated surface coatings that decompose rapidly (undergo vaporization, decomposition, gasification, or partial fusion) on heating with the absorption of heat, so that during the period of their decomposition, the temperature of the shielded surface does not exceed the allowed values.

The first method, which is mainly one of design, does not involve the use of special materials and is not considered here. It is used mainly in cases where protection for long periods of time is required and changes in the dimensions of the outline of the parts being heated cannot be tolerated.

Shielding using the second method is designed for shorter periods of time and usually consists in applying coatings and linings of more heat-resistant materials.

The selection of heat-shielding materials is determined not only by their thermophysical parameters (thermal conductivity, refractoriness, temperature conductivity, heat resistance, etc.) but also by the character of the chemical reaction with the ambient medium (gaseous corrosion, oxidation with volatilization of oxides) and mechanical strength.

Table III.11 lists the properties of certain heat-shielding materials used in such cases.

10. Fusible and Vaporizable Materials /216

The third method of shielding is mainly used when the change in the shape and size of the outline of the coating on a part is of no particular importance. The coating should ensure the operating efficiency of the article in the course of short time intervals, then break down, provided that the part or structure being shielded remains intact after being exposed to extreme conditions for a short time.

Coatings of this type, i.e., burning, fusible, decomposing or vaporizing ones, remove heat during their decomposition or prevent it from reaching the surface being

Table III.11

Some properties of heat-shielding materials

Material	Atomic (molecular) weight	ρ, g/cm^3	MP, °C	BP, °C	at 20°C			at MP			Type of shielding
					a·10^6, m^2/sec	λ, W/(m deg)	c, kJ/kg deg)	c, kJ/(mole deg)	$q_{vap\ lat}$, kJ/mole	$q_{vap\ tot}$, kJ/mole	
Graphite* (P-0.25)	12	1,72	4730	—	106	130	0,71	—	—	358 (a)	RP, G***
Parographite*	12	2,2	4730	—	175	1,9	0,96	—	—	—	RP
Tungsten	184	19,2	3410	5530	68	169	0,13	34 **	845 **	925 **	RP, VAP
Titanium carbide (TiC)	60	4,9	3150	—	13	36	0,56	—	—	—	RP
Boron nitride (BN)	25	2,3	3000	3130 (a)	29	32	0,49	—	—	791 (a)	RP, G
Tantalum	181	16,6	3000	5300	25	54	0.13	32 **	770 **	850 **	PR, VAP
Zirconium dioxide	123	5,3	2680	4100 (c)	-0,28	1,8	0,50	—	—	1185 (s)	RP, G
Molybdenum	96	10,2	2620	4830	52	137	0,26	42	565	675	RP, VAP
Niobium	93	8,57	2470	4930	22	52	0,27	35	700	771	RP, VAP
Beryllium oxide	25	2,88	2450	3030 (a)	83	240	1.0	—	—	290 (c)	RP, G
Aluminum oxide	102	3,8	2050	3660 (a)	13	41	0,84	—	—	3270 (s)	RP
Silicon dioxide	60	2,2	2000	2770 (a)	0,72	1,4	0.89	—	—	864 (s)	RP, G
Beryllium	9,0	1,84	1290	2500	—	—	—	31	320	353	VAP
Lithium	6,9	0,534	180	1370	—	—	—	29	160	164	VAP
Camphor ($C_{10}H_{16}O$)	152	0,99	180	210	—	—	—	~320	59	110	VAP
Naphthalene ($C_{10}H_8$)	128	1,15	80	220	—	—	—	210	44	56	VAP
Biphenyl ($C_{12}H_{10}$)	154	1,15	70	260	—	—	—	220	48	59	VAP
Ammonium chloride	54	1,53	335	335 (dec)	—	—	—	104	176 (dec)	205 (dec)	G
Aluminum nitride (AlN)	41	3,5	2430	2490 (a)	—	—	—	58	612 (dec)	624 (dec)	G

---

* λ and a - in a direction perpendicular to the surface of pressing or deposition; λ and a - in a direction parallel to the surface of pressing or deposition; for boron nitride, one-half as much; for graphite, twice as much; for pyrographite, 200 times as much.

** At 3000 K.

*** RS - refractory shielding; VAP - vaporization shielding; G - gasification shielding.

shielded. They are called "sacrifice" coatings ("sacrificed" to preserve the main article). They are also known as ablation (ablative) coatings.

Table III.11 also lists certain materials used for creating a "sacrifice" shield.

The mechanism of such shielding is different under different conditions and is frequently based on several simultaneous processes, i.e., gasification, vaporization, decomposition, fusion, chemical reaction with the medium, washing out, transpiration, etc.

The most economical and workable shielding materials also include polymer resins, either unfilled or reinforced with fillers, and compositions based on these resins.

The shielding capacity of such materials is considerably increased when they form decomposition products in the form of a carbonized layer. However, not all polymers exhibit the same behavior in this respect.

As an example, Table III.12 lists data on the ability of certain substances to undergo carbonization, estimated by means of the so-called coking value (CV).

Table III.12

Coking values (CV) of certain organic substances

Substance	Elemental composition, %				CV . %
	C	H	O	N	
Phenol-formaldehyde resin (novolac 18)	76	6	18	—	56
Furyl alcohol polymer	39	46	15	—	49
Polyacrylonitrile	43	43	—	14	44
Aniline-phenol-formaldehyde resin (resol resin 211)	79	6	15	—	39
Phenol-benzaldehyde resin	52	44	4	—	37
Polybutadiene	40	60	—	—	12
ED-5 epoxy resin	40	46	14	—	10

The coking value is the mass of the solid residue (expressed in percent) /217
after heating the substance at 1170-1220 K at a pressure of 1-2 at for 7-10 min, referred to the mass of the initial polymer.

A carbonization tendency is exhibited primarily by polymers containing five- or six-membered rings similar to the hexagons of graphite with a C-C distance of 1.415 Å.

11. Fireproofing and Fire-Resistant Coverings

Fire-resistant coverings are an obligatory structural element of ships for preventing fire and limiting its spread over the ship.

In degree of flame resistance, ship fireproof coverings are divided into three /222
types: fireproof (type A), fire-retardant (type B), and separatory (type C) (Table III.13). Type A coverings must have flame and smoke impermeability for 1 h. Type B flame retardants must be impermeable to flame for 0.5 h. Type C coverings must be made of noncombustible materials.

Structurally, most fireproof coverings consist of a supporting base (steel, light alloy) insulated by a noncombustible heat-insulating covering in the form of preformed elements or mastic insulation.

Tables III.14 and III.15 list the properties of some types of such insulation.[11]

Figure III.7 shows different variants of modern ship fireproof structures using new types of insulation, including the panelboard type.

Figure III.7 (I) shows fireproof ship coverings with insulation of marinite panels, and Fig. III.7 (II) shows fireproof coverings with mineral wool insulation, used in foreign shipbuilding.

Figure III.7 (III) shows structural diagrams of standard fireproof coverings approved for use in U.S. shipbuilding.

Table III.13

Classification of fireproof ship coverings based on the degree of fire resistance according to international requirements MK 1960

Ship fireproof coverings	Types of fireproof coverings	Properties of types of fireproof coverings on ships according to international requirements					
		Criteria for estimating the limit of fire resistance in time, min				Structural base	Insulation
		Standard fire resistance test	Flame impermeability	Smoke impermeability	Heating to allowed temperature		
Fireproof (type A)	A-60	60	60	60	60	Steel or equivalent material* reinforced with stiffeners	Noncombustible material**
	A-30	60	60	60	30		
	A-15	60	60	60	15		
	A-0	60	60	60	0		
Flame-retardant (type B)	B-30	30	30	-	30	Inner layer made of noncombustible material	Any material
	B-15	30	30	-	15	Noncombustible material (including material of parts for assembly of panels)	
	B-0	30	30	-	0		
Partition (type C)	C	-	-	-	-		

[*] Any material which by itself or thanks to the insulation covering it possesses structural properties and impermeability that make it equivalent to steel, after exposure to fire, in accordance with the standard fire resistance test.

[**] Material which does not burn and does not evolve inflammable gases in amounts sufficient for their ignition by a foreign flame or other ignition source on heating to 750°C. Any other material is considered combustible.

Table III.14

Fire resistance limits of partitions on passenger ships according to the international recommendations of IMKO

Adjoining compartments	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Control posts	B-0[1]	A-0	A-0	A-0	A-0 B-0[2]	A-60	A-60	A-60	A-0	A-0	A-60	A-60	A-60	A-60
2. Connections between decks	—	A-0[1]	A-0	A-0	A-0	A-0	A-15 A-0	A-30 A-0	A-0	A-0	A-15	A-30	A-15 A-0	A-30
3. Corridors	—	—	C	A-0	A-0 B-0	B-0	B-15 B-0	B-15 B-0	B-0	A-0	A-15	A-30	A-0	A-30 A-0
4. Areas for boarding lifeboats and rafts for releasing them	—	—	—	No requirements[3]		A-0	A-0	A-0	A-0	A-0	A-0	A-15	A-0	A-15 A-0
5. Open spaces on decks	—	—	—	—	—	A-0 B-0	A-0 B-0	A-0 B-0	A-0 B-0	A-0	A-0	A-0	A-0 B-0	A-0 B-0
6. Living quarters with a slight fire hazard	—	—	—	—	—	B-0 C	B-15 C	B-15 C	B-0 C	A-0	A-15 A-0	A-30	A-0	A-30 A-0
7. Living quarters with a moderate fire hazard	—	—	—	—	—	—	B-15 C	B-15 C	B-0 C	A-0	A-15 A-0	A-60	A-15 A-0	A-60 A-15
8. Living quarters with a great fire hazard	—	—	—	—	—	—	—	B-15 C	B-0 C	A-0	A-30 A-0	A-60	A-15 A-0	A-60 A-15
9. Sanitary and similar quarters	—	—	—	—	—	—	—	—	C	A-0	A-0	A-0	A-0	A-0
10. Reservoirs and compartments for auxiliary mechanisms presenting a slight fire hazard or none at all	—	—	—	—	—	—	—	—	—	A-0[1]	A-0	A-0	A-0	A-0
11. Space for auxiliary mechanisms, cargo space, special category compartments, cargo and other similar compartments of moderate fire hazard	—	—	—	—	—	—	—	—	—	—	A-0[1]	A-0	A-0	A-30[4] A-15
12. Machine compartments and main galleys	—	—	—	—	—	—	—	—	—	—	—	A-0	A-0	A-60
13. Storerooms, workshops, pantries, etc.	—	—	—	—	—	—	—	—	—	—	—	—	A-0[1]	A-0
14. Other quarters for storing inflammable liquids	—	—	—	—	—	—	—	—	—	—	—	—		A-30[4] A-15

[1] If an adjacent compartment belongs to the same numerical category, fireproof coverings of a specified fire resistance are not obligatory between them.

[2] The presence of two values of fire resistance limits in the same space of the table signifies that the lower one is used in compartments protected with an automatic fire-extinguishing sprinkler system (this system is also used for detecting fire).

[3] No special requirements are imposed on the material and fire resistance of the protective covering.

[4] A lower fire resistance limit may be adopted if one of the adjacent compartments is protected by a sprinkler system.

Table III.15

Types of insulation for ship fireproof coverings, used in Soviet and foreign shipbuilding

Insulation	Insulation produced in	Basic properties of ship fireproof insulation						
		Insulation type	Density, kg/m^3	Thermal conductivity coefficient, kcal/(m h °C)	Thickness, mm	Mode of attachment to base of structure	Lining and finishing of insulation	Chief components of insulation
Marinite	England	Panels	570-770	0.095	6.3-30	Using channels, angles, bolts, screws and pins	Plywood, plastic, metal, leather substitutes, Getinaks, PCV tiles, etc. Materials not more than 1.5 mm thick	Asbestos, lime, diatomaceous earth, inorganic binder
Neptunite	GDR	"	680-730	0.167	13-20	Same	Same	Asbestos and magnesia cement
Asbosilite	USSR	"	700-790	0.160	14, 20, 26	"	"	Asbestos and lime-silica binder
Navilite	Denmark	"	550-750	0.085	9.5-25.4	"	"	Pressed laminated asbestos and inorganic binder
Vulcanite	Bulgaria	"	410-700	0.090	12-24	"	"	Portland cement, light perlite, long-fibered asbestos
Limpetasbestos	England	Mastics	120-200	0.046-0.085	12-75	Spray coating with compressed air over anchor studs with a fastened metal grid	Decorative finishing with special mastic	Fluffy asbestos, dry binder, water
Asbestos cement	USSR	"	300-400	0.086-0.096	30-60	Same	Covering with cambric, painting, enclosing	Fluffy asbestos, portland cement, water
Extruded asbestos	GDR	"	300	0.090	24-60	"	Enclosing with zinc-plated sheets 1 mm thick	Fluffy asbestos, sodium silicate, water
Thermovermiculite	USSR	"	700-800	0.200	20-40	Throwing on by hand	Covering with cambric and painting	Water solution of alumina cement and fired vermiculite

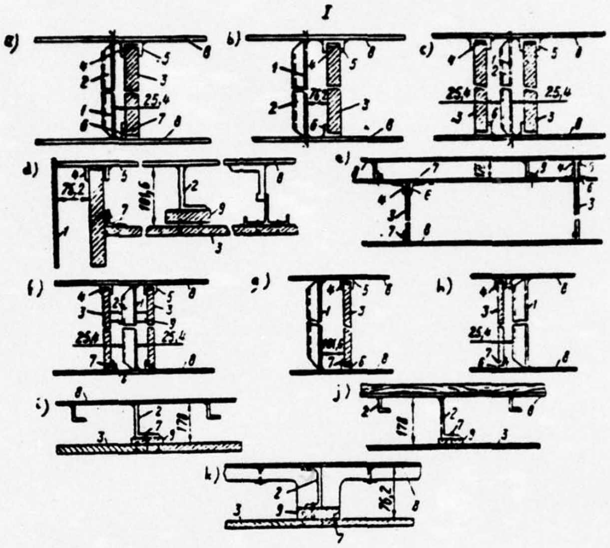

Fig. III.7. Different variants of modern fireproof ship structures using new types of insulation materials /223

I - fireproof ship coverings with marinite panel insulation:

a - steel partitions with one-sided insulation by panels, fastened or free-standing, of the following thickness: 30 mm for type A-60, 25.4 mm for type A-30, 12.7 mm for type A-15; b - steel partitions with one-sided insulation by free-standing panels of the following thickness: 25.4 mm for type A-60, 19.1 mm for type A-30, 12.7 mm for type A-15; c - steel partitions with two-sided insulation by free-standing panels of the following thickness: 12.7 mm for types A-60 and A-30, 9.5 mm for type A-15; d - steel deck with insulation of deckhead by panels of the following thickness: 12.7 mm for type A-60, 9.5 mm for types A-30 and A-15; e - partitions made of panels 22.2 mm thick for type B-15 and 15.9 mm for type C; continuous deckhead of type B made of panels 6.3 mm thick; f - partitions of aluminum alloy with two-sided insulation by panels 19.1 mm thick for all types A and 12.7 mm thick for all types B; g - aluminum alloy partitions with one-sided insulation by panels 15.9 mm thick for types A-30, A-15 and A-0; h - partitions with base of aluminum and one-sided insulation by panels 9.5 mm thick for types B-15 and B-0; i - decks of aluminum alloy without deck covering from above with insulation of deckhead by panels of the following thickness: 19.1 mm for type A-60, 9.5 mm for type A-0 and 6.3 mm for types B-15 and B-0; j - decks of aluminum alloy (deck coverings of teak - 38 mm, "durasteak"or oak - 25.4 mm, neoprene - 6.3 mm, set on 4.8 mm latex) with insulation of deckhead of panels 15.9 mm thick for types A-60 and A-30 and 12.7 mm thick for types A-15 and A-0; k - decks of aluminum alloy for hydrofoils with insulation of panels 12.7 mm thick and Roxyl mineral wool 31.7 mm thick for type A-60.

1 - base of partition; 2 - stiffener; 3 - panel; 4 - 6.3 mm air gap; 5 - channel; 6 - angle iron; 7 - zinc-plated screw; 8 - deck; 9 - marinite laths 25.4 x 76.2 mm

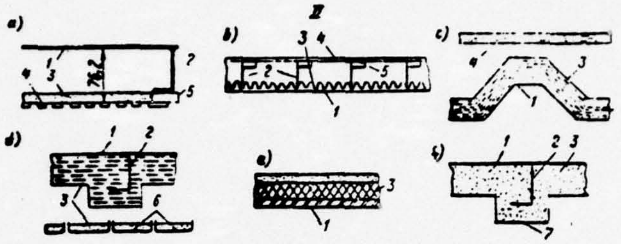

Fig. III.7. II - fireproof coverings with mineral wool insulation, used in foreign shipbuilding: a - fireproof acoustic insulation of type A-60 deckhead with panels of perforated marinite (9.5 mm) and Roxyl board (25.4 mm); b - insulation of type A-60 steel partitions with Navilite panels (15.9 mm) and Rockwool board (20 mm); c - insulation of type A-60 steel partition in stairway enclosures, shafts, elevators, etc. with mineral wool 60 mm thick ($\rho = 125$ kg/m^3) and marinite panel (19.1 mm) coated with noninflammable plastic (1.5 mm); d - insulation of type A-60 deckhead in public spaces and cabins with mineral wool 65 mm thick ($\rho = 125$ kg/m^3) and aluminum alloy cartridges with 20-mm mineral wool ($\rho = 80$ kg/m^3); e - insulation of type A-60 steel decks at control posts with cement (10 mm), mineral wool monoblock ($\rho = 260$-300 kg/m^3) 25 mm thick, Semtex deck covering (15 mm); f - insulation of type A-60 deckhead in machinery and boiler spaces, airconditioning, etc. with mineral wool 65 mm thick ($\rho = 125$ kg/m^3) covered with galvanized iron (1 mm). /224

1 - base of partition or deck; 2 - stiffeners of base; 3 - mineral wool in sheets; 4 - insulation panels; 5 - panel lathing; 6 - cartridges; 7 - galvanized iron

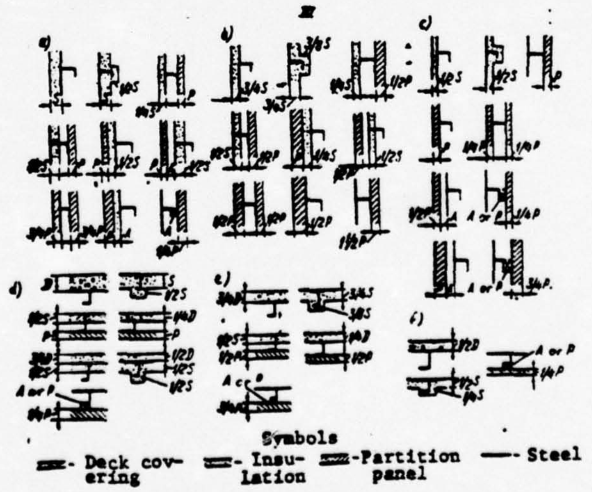

Fig. III.7. III - structural diagrams of standard fireproof coverings approved for use in U.S. shipbuilding: a - A-60 partitions; b - A-30 partitions; c - A-15 partitions; d - A-60 decks; e - A-30 decks; f- A-15 decks.

D - thickness of deck covering for type A-60; S - thickness of structural insulation for type A-60; P - thickness of partition panel for type B-15; A - air gap, 25.4 mm

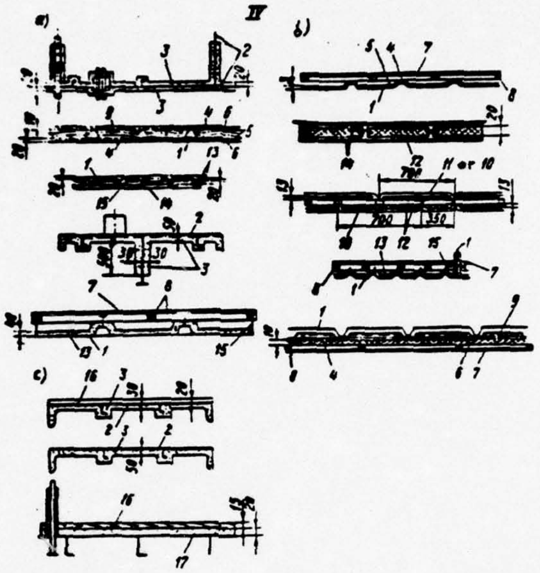

Fig. III.7. IV - standard fireproof designs approved by the USSR Register for use on *Soviet ships: a* - A-60 fireproof partitions; b - B-30 fire-retarding partitions; c - A-60 fireproof decks

1 - sheet steel, 3 mm; 2 - sheet steel, 5 mm; 3 - spray-coated asbestos cement insulation; 4 - asbestos board; 5 - 0.05 mm foil; 6 - 1-mm sheet steel; 7 - 2-mm laminate; 8 - wooden lathing, 30 x 40 mm; 9 - metal lathing, 25 x 25 x 3 mm; 10 - AMG-5 sheets 2 mm thick; 11 - sheet steel, 2 mm; 12 - asbestos glass; 13 - asbestos perlite; 14 - plywood, 8 mm; 15 - M8-10 bolt; 16 - "Neva-ZU" mastic; 17 - vermiculite concrete

Figure III.7 (IV) gives standard fireproof designs approved by the USSR Register for use on Soviet ships.

Fireproof coatings which are formed on the surface of the protective material in the form of a layer stable to 2200-2700°C and, for short periods of time, to 3200°C, are obtained by applying on the surface of the fire-resistant base one of the compositions shown in Table III.16.

Table III.6

Compositions of refractory coatings

Components	No. of composition		
	1	2	3
	Content, parts by weight		
Carborundum	70	40	70
Anatase	70	60	30
Water glass	8	3	
Water	8	5	6

A two-layer foam-ceramic covering has been successfully tested as a heat-shielding covering: it was made up of one layer of dense fireproof concrete 4.7 mm thick (consisting of 30% high-alumina cement + 70% of fused quartz) and a second layer of porous ceramic 23.5 mm thick (of fused SiO_2), prepared by foaming and impregnated with ethyl silicate then acid-treated to convert it into the gel. /224

The weight of such a covering is 24.4 kg/m^2.

Figure III.8 shows the temperature of the inner wall when the outer wall is heated to 1650°C and the influx of heat is ~700 kcal/m^2 sec.

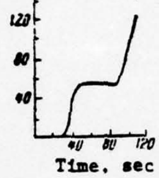

Fig. III.8. Effect of duration of external heating on the temperature of the outer wall of a foam ceramic covering

An effective heat-insulating coating protecting the Mo surface from oxidation is a coating of the composition $MoSi_2/SnAl$. It has the properties of silicide and aluminide coatings. The coating is obtained by immersing a bar of Mo or Mo alloys for several hours in a silicon-saturated SnAl melt. The temperature of the melt is 900°C. As a result of the treatment, a porous layer of $MoSi_2$ whose pores and cracks are filled with SnAl alloy is formed on the surface.

The rate of formation of the coating depends on the Sn/Al ratio (Fig. III.9).

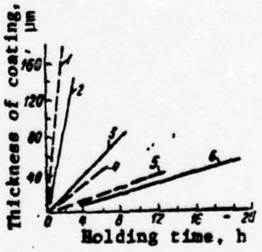

Fig. III.9. Thickness of coating vs time of holding at 900°C in SnAlSi melt

--- MoTiZr alloy; ——— pure Mo. Ratio Sn:Al = 70:30 - (1). 1 - Sn:Al = 70:30; 2, 4 - Sn:Al = 80:20; 3, 5 - Sn:Al = 90:10; 6 - Sn:Al = 95:5.

The optimum thickness of the coating for shielding Mo from oxidation is 80-150 µm. After 2500 h of service in air at 1200°C, the coating on the Mo - 0.5 Ti - 0.08 ZrC alloy consisted of an $MoSi_2$ skeleton and a diffusion layer of Mo_5Si_3. The surface and cracks were coated with an Al_2O_3 film 15-20 µm thick. The pores were filled with oxide and partially with SnAl alloy.

Magnesium, calcium or barium polyacrylate is recommended as the binder for ablation shielding. /225

When exposed to high temperatures, the organic component of the polymer binder burns off, leaving on the surface a thin film of calcium, magnesium or barium oxide which delays further decomposition of the material.

Ca, Mg and Ba polyacrylates (in the amount of 20-60%) may be introduced into the composition of known ablation materials based on phenol-formaldehyde or epoxy resins. According to foreign data, a suspension Sn, Al or Mo antioxidation coating is used for structural panels, heat shields of aircraft leading edges, and other parts of tantalum alloys. The suspension consists of tin, aluminum and molybdenum powders and a lacquer solvent. It is applied on an etched or sandblasted surface with a brush and by spraying, dipping, etc. After drying, the surface is subjected to a 0.5-1 h diffusion treatment at 1037°C.

The coating is composed of the intermetallic compound $TaAl_3$ near the base and Sn Al with $MoAl_3$ particles in the distant part. /227

The proportion of the components corresponds to the formulas Sn · 27Al · 5.5Mo and Sn · 27.5Al · 6.9 Mo.

The coating of the first composition, which is applied in one to two layers, has the best wetting properties. The coating of the second composition is more erosion-resistant and applied in a single layer 76-260 µm thick.

III.4. REFRACTORIES

Refractories are different types of materials, mainly nonmetallic ones, whose specific property is the ability to retain a given strength for long periods of time when heated to high temperatures.

According to their refractoriness, they are divided into refractory (1500-1770°C), high refractory (1770-2000°C) and extra-high refractory materials (above 2000°C).

Refractories are divided into groups according to their composition (Table III.17) and porosity (Table III.18).

The following types of refractory articles are distinguished according to the method of forming plastic-formed (from plastics); dry-formed, nonformed or reinforced (from dry, powdered masses of little or no plasticity, including concrete, fused materials, etc.); slip cast (from liquid slip, foam slip, gas slip, thermoplastic slip, etc.); thermoplastic extruded (from masses with thermoplastic additions); hot extruded (from masses heated to the thermoplastic state); fused-cast (cast from the melt); sawed (from natural rocks or fused blocks).

Table III.17

Classification of refractories according to their chemical-mineral composition (GOST 4385-68)

Type	Group	Content of determining chemical components (relative to calcined substance), %
1. Siliceous	Quartz glass	$SiO_2 \geq 99$
	Dinas (tridymite-cristobalite) with lime binder	$SiO_2 \geq 93$
	Dinas (tridymite-cristobalite) with different binders and different additions	$SiO_2 \geq 80$
2. Alumina-silica (low-, medium- and high-alumina)	Semiacid	$Al_2O_3 < 28$; $SiO_2 = 65+85$
	Fireclay	$Al_2O_3 = 28+45$
	Mullite-silica	$Al_2O_3 = 45+62$
	Mullite	$Al_2O_3 = 62+72$
	Mullite-corundum	$Al_2O_3 = 72+90$
	Corundum	$Al_2O_3 > 90$
3. Magnesia	Magnesite (periclase)	$MgO \geq 90$
	Magnesite (periclase) with different binders	$MgO > 80$
4. Magnesia-lime	Magnesite-dolomite (periclase-lime)	$MgO > 50$; $CaO \geq 10$
	Dolomite (lime-periclase)	$MgO = 35+50$; $CaO = 45+70$
	Stabilized dolomite (periclase-alite)	$MgO = 35 \div 65$; $SiO_2 = 6+15$; $CaO = 15+40$; $CaO : SiO_2 = 2,7-2,9$
	Lime	$CaO > 70$
5. Magnesia-spinallide	Magnesite-chromite (periclase-chromite)	$MgO > 60$; $Cr_2O_3 = 5+18$
	Chromomagnesite (chromite-periclase)	$MgO = 40+60$; $Cr_2O_3 = 18+30$
	Chromite	$MgO < 40$; $Cr_2O_3 > 25$
	Periclase-spinel	$MgO = 40+80$ $Al_2O_3 = 15 \div 55$
	Spinel	$MgO = 25+40$; $Al_2O_3 = 55+70$
6. Magnesia-silicate	Periclase-forsterite	$MgO = 65+80$; $SiO_2 \geq 10$
	Forsterite	$MgO = 50+65$; $SiO_2 = 25+35$
	Forsterite-chromite	$MgO = 45+60$; $SiO_2 = 20+30$; $Cr_2O_3 = 5+15$

Table III.17 continued

Type	Group	Content of determining chemical components (relative to calcined substance), %
7. Carbonaceous	Graphitized carbonaceous	$C > 98$
	Nongraphitized carbonaceous (coaly)	$C > 85$
	Carbon-containing	$C\ 5+70$
8. Silicon carbide	Recrystallized silicon carbide	$SiC > 90$
	Silicon carbide with different binders	$SiC > 70$
	Silicon carbide-containing	$SiC\ 20+70$
9. Zircon	Zirconia (baddeleite)	$ZrO_2 > 90$
	Baddeleite-corundum	$ZrO_2 > 30$, $Al_2O_3 < 65$
	Zircon with different binders and different additions	$ZrO_2 > 35$, $SiO_2 > 18$
10. Oxide	Products made up of oxides (BeO, MgO, CaO, Al_2O_3, ZrO_2, TiO_2, UO_2 etc)	Maximum content of determining oxide
11. Non-oxygen	Products made up of nitrides, borides, carbides (except SiC), silicides and other compounds containing no oxygen	Maximum content of compounds containing no oxygen

Table III.18

Porosity groups of refractories

Group	Open porosity, %	Group	Open porosity, %
Extrahigh-density	up to 3	Ordinary:	
High-density	3—10	Subgroup I	20—24
Dense	10—16	Subgroup II	24—30
Compacted	16—20	Lightweight	45—85 *
		Ultralightweight	above 85 *

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* Total porosity.

Table III.19

Magnesia refractories (MR)

Index	Fired MR		
	At ordinary temperatures	At elevated temperatures	Without binders
P_t, %	18,7	16,3	15,2
ρ, g/cm^3	2,88	2,91	3,08
ρ_{app}, g/cm^3	3,45	3,46	3,63
σ_c, kg/cm^2	840	780	820
t_{soft}, °C	1550	>1650	>1650
	Composition, %		
SiO_2	2,48	0.42	1,01
Al_2O_3	0,45	0,18	6,12
Fe_2O_3	0,33	0,07	6,09
CaO	1.04	1.48	0.85
MgO	94,84	97,85	77,85
Cr_2O_3	—	—	7,07

Depending on the type of heat treatment, the following refractory products are distinguished: fired, unfired, dried, sometimes with heating to 250-400°C; hot-extruded, fired after extrusion; fused-cast, and annealed after casting.

Since the requirements for the stability of refractories increase because of ever more severe service conditions (components of gas turbines, magnetogasdynamic generators, plasmatrons, etc.), new refractory compositions are being continuously developed, mainly based on highly refractory oxide and intermetallic compounds and their combinations. Such new compositions include, for example, high-magnesia and chromia-magnesia refractories (Table III.19).

12. Porous and Lightweight Refractories

Heat insulation at high temperatures (for example, in furnace chambers) is also achieved by using, in addition to charging insulation, various lightweight refractory articles combining a low thermal conductivity with a high refractoriness and satisfactory structural strength. These materials are called heat-insulating, porous or lightweight refractories.

Table III.20 shows the properties of certain refractories. /230

The term porous (or sometimes lightweight) is applied to refractories of low apparent density (ρ = 0.4-1.4 g/cm^3), caused by their cellular structure, with a large number of statistically uniformly distributed open or closed cavities (pores)./231

This structure can be obtained by numerous technological methods, the most important of which are the following:

(1) introduction of a porous filler - natural or synthetic - into the initial mass;

(2) blowing or heat treatment of the entire mass or its individual components;

Table III.20

Some properties of heat-insulating refractories

Property	Lightweight fireclay			BL-08 lightweight foam	BL-04 ultra-lightweight material	Dinas lightweight material (SiO_2>91%)	PD-350 and PD-450 foam diatomaceous brick
	AL-1.3	BL-1.3	BL-1.0				
Refractoriness, °C, not below	1750	1670	1700	1670	1690	1670	-
ρ, g/cm^3, not above	1.3	1.3	1.0	0.8	0.4	1.2	3.65-4.2
P, %	-	-	59	-	82	-	
σ_c, kgf/cm^2, at least	45	30		20	10	30	6-8
Additional shrinkage, %	1.0	2.0	0.5	1.0	0.4	-	-
At temperature, °C	1400	1350	1350	1250	1250	-	-
λ, kcal/m h °C)	0.64	0.53	0.48	0.40	0.18	-	0.11-0.12
At t_{av}, °C	780	720	760	700	515	-	350
Maximum working temperature, °C	1400	1300	1200	1200	1200	1500	900

(3) introduction of additives leaving pores in the initial mass and their subsequent removal (by burning, sublimation, vaporization, dissolution);

(4) mineral formation during the firing, associated with an increase in porosity;

(5) introduction of air into the suspension or melt, and freezing of the air bubbles formed;

(6) formation of gas bubbles in the suspension or melt as a result of chemical reactions between the additives introduced or their decomposition.

In practice, the following three methods are the most common ones:

(1) method of burning additives, based on the introduction into the initial charge of various organic substances (sawdust, coke, coal, straw, etc.) which are subsequently burned off; the proportion of the additives to the main mass determines the properties of the product;

(2) method of foaming, based on mixing of a suspension of the refractory material with a foaming agent or with a foam prepared separately and in subsequent solidification by drying and firing of the cellular structure obtained;

(3) method of chemical pore formation based on swelling of the initial mass by the gas evolved during chemical reactions as a result of the interaction or decomposition of the additives introduced into the mass. The combinations of gas forming agents are different: carbonates + acids (for example, $CaCO_3$ + HCl); metals + acids (for example, Zn + HCl or Al + H_3PO_4); metals and alkalis (for example, Al + NH_4OH); foam polyurethanes; peroxides, etc.

Table III.21

Principal characteristics of certain porous refractories

Property	Type of material*								
	1	2	3	4	5	6	7	8	9
ρ_{app}, g/cm^3	0,5–0,9	0,3–0,7	0,4–0,7	1,48	—	1,5	—	—	2,42
P_t, %	79–81	90–63	85–78	50,5	31	—	55	35	40
K_g, 1 m/(m^2 h mm H_2O)	85–2,5	20–0,3	—	41	0,1	—	4	117	—
σ_c, kgf/cm^2	24–85	15–90	15–45	45	1150	—	370	85	700
SS, °C	—	1540–1580	1620–1750	1380	>1800	1400	1500	1270	>1800
Heat resistance	1/850 **	8–10/850 **	>20/850 **	6/1600 ***	6/1600 ***	1–2/850 **	1/1000 ***	15/1000 ***	>40/1000 **
A_s, %	—	—	—	0,6–0,7	—	0,7–1,5	0,0	0,7	0,1
$a\cdot10^6$/°C	15,5	3,7	2,5	—	—	12,7	—	—	—
λ, kcal/(m h deg)	—	—	—	—	—	0,7–0,9	—	—	—

Table III.21 cont.

Property	Type of material*									
	10	11	12	13	14	15	16	17	18	19
ρ_{app}, g/cm^3	0,69	0,00	0,52	0,75	1,46–1,52	1,18	0,33	0,39–0,40	1,0–1,23	0,49–1,39
P_t, %	83	85	84	79	55 (app)	67	86	82–83	47–55/app	81–48
K_g, 1 m/(m^2 h mm H_2O)	—	—	—	—	23–35	—	—	—	28–40	21–0,1
σ_c, kgf/cm^2	130	45	12	38	28–44	23	14–21	29–36	40–80	55–370
SS, °C	1570	1600	—	1590	1490	—	—	—	1620–1640	1210–1380
Heat resistance	5/1000 ***	10/800 ***	5/800 ***	—	—	—	>30/1000 ***	>30/1000 ***	—	3–20/950 *
A_s, %	0,5	—	—	0	0,4	4,0	—	—	—	—
$a\cdot10^6$/°C	—	—	—	0	—	1,27%	1,8–2	1,6–1,8	13	1,4–2,2
λ, kcal/(m h deg)	—	0,5	0,5	0,36–0,48	0,51	0,28	0,09–0,25	0,16–0,24	0,68	—

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* Types of materials: 1 - SiC with siliceous binder; 2 - SiC with aluminosilicate binder; 3 - SiC with nitride binder; 4 - BeO with 20% petroleum coke; 5 - foam ceramic with BeO; 6 - MgO porous ceramic; 7 - porous zirconia foam ceramic; 8 - porous zirconia ceramic with burning-off additions; 9,10 - foam corundum with prefired alumina; 11 - lightweight corundum without phosphates, fired at 1650°C; 12 - lightweight corundum with phosphate, fired at 1100°C; 13 - foam corundum with Al + HCl gas-forming agent; 14 - forsterite lightweight material with 30% petroleum coke; 15 - porous chromomagnesite; 16,17 - foam quartz with porous plastic based on alumina phosphate binder; 18 - lightweight Dinas; 19 - lightweight cordierite foam.

** Water cooling. Numerator - number of heat cycles; denominator - temperature.

*** Air cooling. Numerator - number of heat cycles; denominator - temperature. K_g - gas permeability; P_t - true porosity; A_s - additional shrinkage.

A porous high-temperature refractory based on aluminum oxide is obtained by adding silicon nitride (38% N) to its composition.

The additive lowers the firing temperature (to 1300°C) and raises the working temperature (to 1500-1800°C), while the high heat-insulating properties and mechanical strength of the refractory are preserved. The SiN content of the refractory is 1 to 30% of corundum. The foaming agents are surfactants or a mixture of aluminum powder and slaked lime.

Porous refractories can be obtained with practically any base among those used for preparing dense refractories.

Table III.21 and Fig. III.10, which illustrate a few of the large number of known examples, give an idea of this possibility.

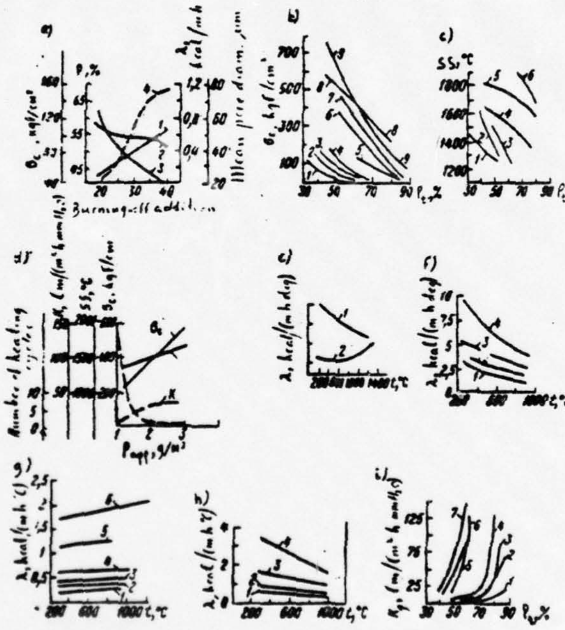

Fig. III.10. Some characteristics of various types of highly refractory porous ceramic: a - effect of the content of burning-off additives on the properties of lightweight dinas.

1 - porosity; 2 - thermal conductivity; 3 - strength; 4 - pore size;
b - compressive strength for various porous high refractories vs porosity and method of pore formation.
Method of burning-off additives: 1 - MgO; 2 - BeO; 3 - ZrO_2; 4 - Al_2O_3; foam method: 5 - SiC; 6 - MgO; 7 - BeO; 8 - ZrO_2; 9 - Al_2O_3;
c - temperature of the start of softening (SS) under load for various porous high refractories vs porosity and method of pore formation.

Fig. III.10 continued

Method of burning-off additives: 1 - ZrO_2; 2 - BeO; 3 - Al_2O_3; blowing method: 4 - ZrO_2; 5 - Al_2O_3; 6 - BeO;
d - certain properties of zirconia lightweight foam material vs apparent density.
1 - σ_c; 2 - SS °C; 3 - K; -·-·- number of heat cycles;
e - thermal conductivity of sillimanite lightweight material vs pore size, porosity and temperature.
1 - fine pores, 45% porosity; 2 - large pores, 59% porosity;
f - thermal conductivity of beryllium foam ceramic vs porosity and temperature.
Porosity: 1 - 78%; 2 - 71%; 3 - 63%; 4 - 50%;
g - thermal conductivity of zirconium foam ceramic vs porosity and temperature.
Porosity: 1 - 80%; 2 - 70%; 3 - 64%; 4 - 53%; 5 - 28%; 6 - 0.0%;
h - thermal conductivity of corundum foam ceramic vs porosity and temperature.
Porosity: 1 - 87%; 2 - 82%; 3 - 69%; 4 - 60%;
i - gas permeability of various porous high refractories vs porosity and method of pore formation.
Foam method: 1 - SiC; 2 - Al_2O_3; 3 - BeO; 4 - ZrO_2; method of burning-off additives: 5 - BeO; 6 - Al_2O_3; 7 - ZrO_2.

III.5. SYNTACTIC MATERIALS

The term syntactic (from syntaktikos - putting together) is applied to composite structural materials of low density, obtained by mechanical mixing of hollow closed microspheres (thin-walled hollow globules) with a binder capable of solidifying (usually, a synthetic resin) and converting the mixture into a closed monolithic cellular mass of foam plastic type. Because of this property and also their low thermal conductivity, these materials are considered in this chapter. /235

However, in contrast to foam plastic, the material obtained has much higher indices of mechanical strength, particularly a high compression resistance.

By varying the material of the microspheres, their diameter and wall thickness, the binder composition and the conditions of preparation, one can obtain syntactic materials possessing diverse properties, including different thermal conductivity indices. Table III.22 shows certain generalized data on combinations that have been used in practice.

The Soviet industry produces microspheres of glass (TU 6-11-156-70) and phenol-formaldehyde resins (TU V-166-70). Their principal properties are as follows:

Material of microspheres	Bulk density, g/cm^3	Density, g/cm^3	Particle size, μm	Fusibility, %
Glass	0.10-0.20	0.22-0.40	10-200	98
Phenol-formaldehyde	-	0.20-0.36	10-300	90

Table III.23 gives the properties of several syntactic compositions made up of glass microspheres with an epoxy resin (according to foreign data).

Tables III.24-III.27 and Fig. III.11 below give certain characteristics[10] of syntactic compositions with binders, epoxy resin (EDS and EDM materials) and polyester resin (SPS and SPM materials).

Table III.22

Some properties of syntactic compositions

Property	Nature or limits of values
Material of microspheres	**Glass, ceramic, synthetic resins, aluminum, titanium**
Binder material	**Various thermosetting and thermoplastic polymers**
Diameters of microspheres	**10-500 μm (glass, resins, ceramics); 2-15 mm (aluminum, titanium, resins)**
Wall thickness	**Depending on the manner of preparation, usually 1-3% of diameter**
Packing density (ratio of volume of microspheres to total volume of material)	For one-dimensional spheres, 0.65-0.67; two-dimensional ones, ~0.7-0.8; three- and four-dimensional spheres, ~0.90 and ~0.95
Density of hardened syntactic composition, kg/m^3	500-800
Absorption of water under pressure, %	up to 1.0
Strength limits of hardened composition, kgf/cm^2:	
σ_u	100-400
σ_{sh}	100-500
σ_c in linear compression	500-1200
σ_c in volume compression	600-1500
σ_b	100-500
Elastic modulus, $kgf/cm^2 \cdot 10^{-4}$:	
in volume compression	1.5-4.0
in linear compression	2-4
a_i, kgf cm/cm^2	1-7

Table III.23

Some properties of syntactic compositions

Property	Composition withstanding hydrostatic pressure, kgf/cm^2		
	up to 170	up to 315	up to 945*
Nominal density, kg/m^3	560	603	672
Positive buoyancy in seawater (ρ = 102 kg/m^3)	463	417	362
Hydrostatic compression strength $\sigma_{v\ c}$, kgf/cm^2	630-703	840-1050	1260-1470
Volume compression modulus $E_{v\ c} \cdot 10^{-4}$, kgf/cm^2	1.76-2.11	2.11-2.46	3.16-3.52
Linear compression strength $\sigma_{\ell\ c}$, kgf/cm^2	560-598	633-703	1054-1125
Modulus of elasticity in linear compression $E_c \cdot 10^{-4}$, kgf/cm^2	2.11-2.46	2.46-2.81	3.51-3.73
Tensile strength σ_u, kgf/cm^2	105-140	210-281	351-422
Shear strength σ_{sh}, kgf/cm^2	105-140	210-281	351-422
Water absorption, %	no greater than 1% at a pressure up to 703 kgf/cm^2		

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*No deformations were observed after a year's exposure to water at a pressure up to 950 kgf/cm^2.

Table III.24

Some characteristics of Soviet syntactic materials

Property	Type			
	Epoxy resin base		Polyester binder	
	EDS	EDM	SPS	SPM
ρ, kg/m^3	600—800 680	600—800 650	600—750 680	600—750
σ_c, kgf/cm^2	550—900 700	290—500 450	400—600 565	250—400
σ_b, kgf/cm^2	400 380	150—260 215	250 290	100—200
σ_u, kgf/cm^2	250	140	190	50—110
$E_c \times 10^{-3}$, kgf/cm^2	15—27	8—15	12—20	5—10
a_i, kgf cm/cm^2	2—7	1—3	1—2	1—2
$a \cdot 10^{-3}$, m^2/h	0,5—0,6	0,4	—	—
λ, kcal/m h °C	0,1	0,078	—	—
c, kcal/(kg °C)	0,29—0,34	0,29	—	—
$\alpha \cdot 10^6$/deg (50—200° C)	50—80	73—103	—	—

Table III.25

Effect of thermal aging for 150 h on the properties of syntactic materials

Property	Holding temperature, °C								
	160			180			200		
	EDS-6	EDM-5	SPS-1	EDS-6	EDM-5	SPS-1	EDS-6	EDM-5	SPS
σ_c, kgf/cm^2	617	450	625	617	440	607	600	406	410
σ_c, % of initial	88	100	110	88	98	108	80	90	73
σ_b, kgf/cm^2	360	215	250	370	227	92	370	180	94
σ_b, % of initial	95	100	86	97	105	32	97	84	32
Weight loss, %	0	0,16	0,83	0,4	1,8	3,9	1,5	3,7	22,5
Δl, %	0	0	0,28	0,6	0,5	0,8	0,25	0,27	3,7
W_{120} h, %	0,18	0,75	1,10	0,15	0,92	1,75	0,10	0,95	3,9

Initial ρ, kg/m^3: EDS-6 - 680; EDM-5 - 650; SPS-1 - 680.

Table III.26

Dielectric properties of certain syntactic materials

Property	Type of material	
	EDS-5	SPS-1
ρ_v, ohm cm:		
in dry state	$5{,}8 \cdot 10^{14}$	$9{,}6 \cdot 10^{13}$
after 24 h in water at 20°C	$1{,}4 \cdot 10^{13}$	$2{,}2 \cdot 10^{13}$
ρ_s, ohm:		
in dry state	$5 \cdot 10^{14}$—$1 \cdot 10^{16}$	$2{,}8 \cdot 10^{14}$
after 24 h in water at 20°C	$1{,}5 \cdot 10^{9}$—$3{,}2 \cdot 10^{12}$	$1{,}5 \cdot 10^{9}$
$\tan\delta_{10^6}$	0,014—0,017	—
ε	2,1—3,0	3,3
U_{lim}, kV/mm	11	—

Table III.27

Properties of EDS materials with different setting conditions

Property	Setting conditions			
	[illegible]° C, 23		30 ± 2° C, 30	
	EDS I	EDS II	EDS I	EDS II
ρ, kg/m^3	680	740	700	730
σ_c, kgf/cm^2	860	890	700	875
$E_c \cdot 10^{-3}$, kgf/cm^2	18,6	17,7	19	17,2
HB, kgf/mm^2	10,6—12,8	—	9,8—12,2	—
W_{120} h, %	1,0	1,2	1,1	1,3
σ_c after 120 h in water, kgf/cm^2	770	900	750	930

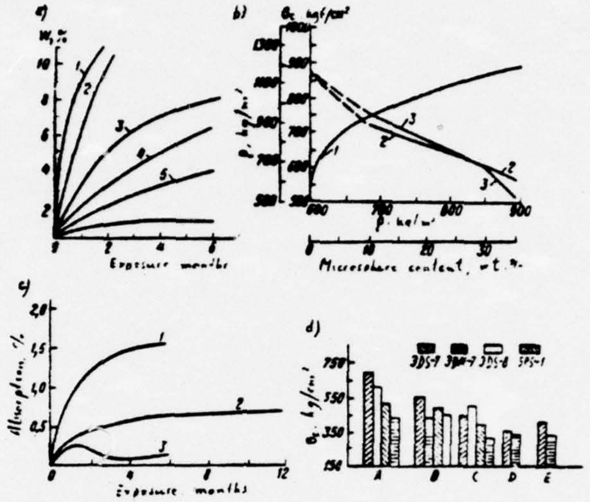

Fig. III.11. Some characteristics of syntactic materials: a - water absorption of syntactic materials. /238
1 - SPS-1; 2 - SPS-1A; 3 - EDM-7; 4 - EDS-6; 5 - EDS-7; 6 - EDS-7A (A - on sized surface);
b - some properties of EDS syntactic compositions.
1 - compression strength σ_c vs apparent density ρ; 2,3 - calculated and experimental curves of apparent density ρ as a function of the microsphere content of the composition;
c - absorption of isopropyl alcohol during prolonged holding.
1 - EDM-7; 2 - EDS-7; 3 - SPS-1;
d - effect of prolonged exposure of syntactic materials to different media on the mechanical strength.
A - initial; B - in benzine, transformer oil, and isopropyl alcohol; C - in carbon tetrachloride; D - in 10% H_2SO_4; E - in 10% alkali. Holding time: EDS - 12 months in all media; SPS - 6 months in all media; EDM - 12 months (C, D, E); EDM - 6 months (B).

/238 According to the authors' data, the content of microspheres in the composition ranges from 10 to 30%. Within these limits, the composition has pouring properties. Above 30% microspheres, molding compositions are obtained. Molding compositions are formed at low pressures (5–20 kgf/cm^2). The critical concentration for glass microspheres with ρ = 0.25–0.28 g/cm^3 is 22-25 wt.%. Optimal physicomechanical properties correspond to the critical concentration.

/239 The chemical stability of syntactic materials is determined by the chemical stability of the binder in a given medium.

/240 Syntactic compositions are of considerable interest in shipbuilding: this is a strong and light structural material of high buoyancy with a low water absorption, good corrosion resistance and a number of other desirable properties.

Adhesive strength of compositions, kgf/cm^2

nature of adhesion	with EDM	with EDS
To metals:		
detachment	10	-
shear	40	87
To fiber-glass plastics:		
detachment	20	-
shear	75	250

Coefficient of linear expansion of compositions ($\alpha \cdot 10^6$/deg)

Temperature, °C	EDS	EDM
50	50	73
100	76	82
150	87	94
200	80	103

The material has satisfactory processing properties and can be processed into articles both before solidification and in the solidified state.

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IV.4. FIBERS AND FIBROUS MATERIALS /303

Fibers is the term applied to flexible, mechanically strong, elongated bodies whose length is at least several orders of magnitude (3-5) greater than their thickness.

Monofil is the term applied to fibers of infinite length. A bundle of fine fibers of indefinitely great length is called a thread.

The assortment of fibers used for technical purposes, including shipbuilding, is very broad. An extensive literature has been devoted to the description of the properties and methods of making fibers, and state standards have been formulated.

The principal types of fibers with practical applications may be subdivided as shown in Fig. IV.22.

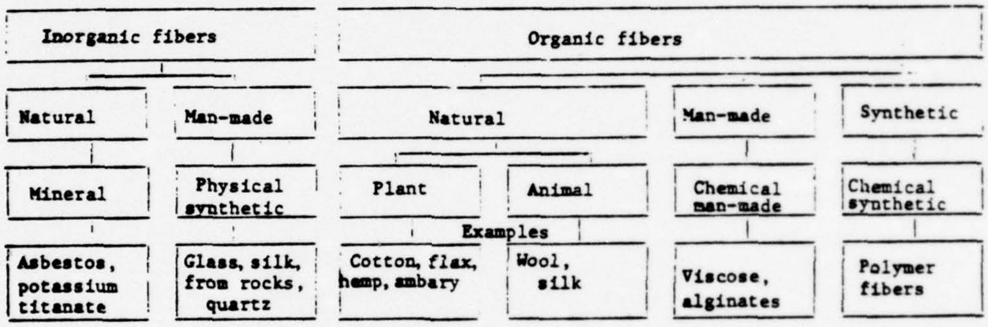

Fig. IV.22. Principal types of fibers having practical applications

The principal characteristics of certain representatives of each of these groups are given in Table IV.34.

Table IV.34 lists certain areas of application of fibers and materials obtained from them in shipbuilding. As is evident from this table, fibers are widely used in shipbuilding. /305

The last decade has been characterized by a definite tendency in shipbuilding to switch from natural fibers to synthetic ones. This is due to the fact that synthetic fibers possess a combination of properties which are of particular interest under the conditions prevailing on ships (high water resistance, resistance to /306 biological attack, high mechanical strength, low density, etc.).

Before discussing the properties of specific representatives of this group of materials, we will mention their useful comparative characteristics, which are somewhat specific in character.

The basic characteristics of the fibers (as physical objects) are their thickness and mechanical strength.

Table IV.34

Some areas of application of fibers in shipbuilding

Main function	Fibers
Reinforcing materials in composites, including fiber glass plastics	Fiber glass and materials based on it
Netting and rigging materials	Plant fibers (hemp, sisal)
Netting threads, trawl yarn, cordage for trawling purposes, fish nets, ropes	Synthetic fibers (capron, anid, lavsan, polyethylene, khlorin, polyvinyl alcohol, polypropylene)
Rigging and equipment, ropes and lines, cargo slings, mooring lines, towing ropes, lowering and mat lines, sloop ropes, shot lines	Hemp, sisal, capron, lavsan, polyethylene and polypropylene
Heat-insulating materials	Felt, asbestos, synthetic fiber, fiber glass
Material for sizing and equipment of ship compartments - upholstering and furniture fabrics, curtains, shades, decorative and trimming fabrics, carpets, runners	Man-made and synthetic fibers
Technical fabrics, fabrics for engineering equipment, canvas, tarpaulin, coveralls, soft packing, pontoons, inflatable rafts	Cotton (including cotton impregnated with rubber and resins), polyamide and polyester fibers, polyvinyl alcohol fibers (vinol)
Conveyor belts, driving belts, flexible pipes for air and liquids, tire cord	Cotton, viscose, polyamide (capron, anid, nylon), polyesters (lavsan), polyvinyl alcohol (vinol)
Filtering materials and filtering fabrics	Plant fibers, asbestos, polymer fibers, nitron, khlorin
Electrical insulation materials	Fiber glass, asbestos
Ion exchange and electron exchange materials (*for example, for water* purification)	Chemically treated cellulose, polyvinly alcohol and polyene fibers
Sealing materials, gaskets, gland packings	Plant fibers (hemp), animal fibers (felt), asbestos and compositions based on it, metallic fibers

In accordance with GOST 10878-70, the thickness of fibers is expressed in tex units, which have the dimension of ML^{-1} (g/km).

The thickness T is determined from the ratio

$$T = \frac{m}{L_1} = 1000\,\frac{m}{L}\ \text{tex (g/km)},$$

where m is the mass in g;
L_1 is the length in km;
L is the length in m.

The thickness of fibers less than 1 tex may be expressed in mtex (1 mtex = 0.001 tex = mg/km).

When the thickness is greater than 1000 tex, the designation ktex is used (1 ktex = 1000 tex = kg/km).

The tex system replaced the metric nomenclature, in which the number (N) of the fiber (yarn) was the number of units of length per unit mass (mm/mg; m/g; km/kg), and also the old system of measuring thickness in denier (1 denier is the mass of a fiber 9000 m long, expressed in grams g/9 km).

Another frequently used property of a fiber is its strength (GOST 11970-70).

The strength (breaking stress) in kgf/mm^2 is the ratio of the breaking load to the cross sectional area of the specimen, determined for fibers by means of the relation

$$\sigma_b = P_b N \rho = \frac{1000\, P_b \rho}{T},$$

where P_b is the breaking load, kgf;
N is the number of the thread;
T is the thickness, tex;
ρ is the density, g/cm^3.

The breaking length BKM in kgf·km/kg is a relative strength characteristic, determined by the length of the fiber in kilometers, at which the latter breaks under its own mass.

The BKM is determined from the relation

$$BKM = P_b N \frac{1000 P_b}{T}.$$

The units of fiber strength are correspondingly related as follows:

1 g/denier = 9 g/tex = 9 BKM = 9 ρ kgf/mm^2 = $88.29 \cdot 10^6$ ρ H/m^2, where ρ is the fiber density, g/cm^3.

13. Organic Fibers /307

Organic fibers include fibers of different nature and properties, a common feature of which are the organic compounds in their composition. According to their origin, they are subdivided into natural, man-made and synthetic fibers.

A. Natural and man-made organic fibers

Natural organic fibers are those obtained in finished form as products of the vital activity of animals or plants and requiring relatively little processing, in which the basic properties and nature of the material remain unchanged. Table IV.35 lists the characteristics of certain natural organic fibers.

Table IV.35

Some characteristics of natural organic fibers

Property	Plant			Animal	
	Cotton	Flax	Hemp	Wool	Silk
Length, mm	12—55	5—55	—	30—60	Continuous
Breaking strength:					
kgf/mm^2	25—40	35—95	45—75	14—25	40—60
g/tex	27—44	—	—	9—18	30—40
g/denier	3—4,9	—	—	1—2	3,3—4,5
Breaking length, km	16—53 27—36	23—63 54—72	55—65	10—19	36—43 27—32
Density, g/cm^3	1,50 1,54	1,5	1,4 1,48	1,30 1,32	1,31 1,37
Elongation at rupture, %	8—10	2,5—4	1,6—2,5	30—54 20—40	13—20 15—25
Modulus of elasticity, kgf/mm^2·10^{-2}	4,5—5,5	—	-	2—4,5	8,5—9
Moisture absorption (ϕ = 98%), %	24—27	28	—	21—22	20

Man-made fibers are those obtained from natural organic raw material by extensive processing, but the nature of the initial substance remains the same in the end product. An example is viscose, obtained by chemical processing of cellulose-rich stock. Table IV.36 lists the characteristics of certain man-made organic fibers.

Man-made fibers as well as the synthetic ones discussed below are frequently called chemical fibers.

B. Synthetic fibers /308

Fibers obtained by reprocessing chemically synthesized substances having no analogs in nature (primarily synthetic polymer resins; see Volume II of this handbook, Sudostroyeniye, Leningrad, 1969) are called synthetic. These fibers are very diverse in composition, and, as is evident from some data of Tables IV.37 and IV.38, can surpass natural and man-made fibers in properties. The composition and properties of the initial materials for making synthetic fibers are not cited here, since these questions are discussed in relative detail in Volume II of this handbook.

Shipbuilding fibrous materials of polymer nature (for ropes, lines, fishing equipment, etc.), i.e., polyamide, polyester, and polyvinyl alcohol fibers, are /309
made in foreign countries under different names. They are widely used on our ships made abroad. Table IV.39 lists certain names of these materials.

C. Thermally stable polymer fibers

Among the many synthetic fibers used for various purposes, fibers of highly heat-resistant polymers are materials whose prospective uses in technology are very broad. They include fibers based on aromatic heterocyclic polymers, polyphenylene amides, polyphenylene hydrazides, polyphenylene sulfonamides, polyalkyl terephthalamides, copolyphenylene amides and many others.

Table IV.36

Characteristics of some man-made organic fibers

Property	Alginate	Viscose fibers									
		Hydrate cellulose					cuprammonium		Triacetate		Diacetate Multifilament
		Multifilament	Reinforced filament	Cord filament	Staple		Multifilament	Staple	Multifilament	Staple¹	
					Ordinary	Reinforced					
Breaking strength:											
kgf/m²	26–32	30—37	38—44,0	50—81	35—45	51—68	23—32	16—26	13—15	17—19	14—18
g/tex	14,4—18	13—24	24—29	30—54	23–30	34—40	15–21	11—17	10—12	13—15	12—14
g/denier	1,6—2,0	1,5—2,0	2,6—3,0	3,7—6,0	2,6–3,3	3,8—5,0	1,7—2,3	1,2—1,6	1,2—1,4		1,1–1,5
Breaking length, km	—	—	—	28–55	—	20—28	14—20	—	11—15		
Density, g/cm³	1,78			1,49—1,53			1,52—1,54		1,28—1,33		1,29—1,33
Elongation at rupture, %:											
in wet state	—	19,26	23—29	20—27	19–28	25—29	16—30	35—50	30—40	30—40	35—45
in dry state	6—8	17—25	17—19	10—15	15–23	18—20	10—17	20—28	15—22	19—32	25—35
Initial modulus of elasticity, kgf/mm²·10²	—	3—4	4—5	6—10	4,4—9,3	10—24	5—9	4—6	3—4,8	—	2,6—4,9
GOST certified moisture content, %	11	11	11	11	12	12	—	12,5	4,5	4,5	7
Moisture absorption (φ = 98%), %	52	—	—	27—33	—	—	27—30	27—30	10—12	10—12	10—14
Volume swelling in water, %		74—127	62—70				100—125		12—18		20—25
Thermal stability, °C	—			150			150		250		175
Heat capacity, cal/(g °C)				0,31—0,32				0,32			
Temperature, °C											
of softening	—	—	—	—	—	—	—	—	230—250	230—250	204—245
of fusion (decomposition)				175—205			175—200	175—200	290—300	290—300	230—260
GOST		8871—67 14308—69 TU 6-06-322—71			10546—63 OST 6-9—71			8937—68	16743—71 16744—71	16836—71	

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¹Thermal conductivity, 0.13 cal/(m h °C).

Table IV.37

Some characteristics of synthetic fibers (carbon chain polymers)

Property	Acrylonitrile				Chlorine-containing						
	nitron[1]		Acrilan	Dynel	Khlorin		Saran			Atsetokhlorin	
	Multifilament	Staple	Staple	Staple	Multifilament	Staple[3]	Monofilament	Multifilament	Staple	Multifilament	Staple
Breaking strengths:											
kgf/mm^2	47-56	27-39	27	28-40	19-28	20-28	17-36	<30	24	18-22	19-24
g/tex	40-48	23-30	23	22-31	13-19	12-19	10-21	<18	<14	13-16	14-17
g/denier	4.4-5.3	2.4-3.3	2.5	2.4-3.4	1.4-1.7	1.3-1.9	1.1-2.3	2	1.5	1.4-1.8	1.5-1.9
Breaking length, km	40-50	20-35	-	-	15-25	-	-	-	-	-	-
Density, g/cm^3	1.17-1.19		-	-	1.47-1.60		1.65-1.72			1.4	
Elongation at rupture, %:											
in wet state	-	-	-	-		-	15-25		15-20	-	-
in dry state	15-22	20-28	36	31	19-25	17-25				15-28	22-56
Initial modulus of elasticity, kgf/mm$^2 \cdot 10^{-2}$	6-8	3.5-4	-	-	4-4.6	-	-	-	-	3-4	-
Moisture absorption (at φ 98%), %	1.5-2	3.2-4		1	0.7-0.9		-	0.1	-	2.3-2.5	
Thermal stability, °C	100		235	150	70	-	-	-	-	-	-
Heat capacity, cal/(g °C)	0.36-0.40		-	-	0.25		-	0.32	-	-	-
Thermal conductivity, cal/(m h °C)	-	-	-	-	0.14		-	-	-	-	-
Temperature, °C:											
of softening	-		-	-	80-110		-	-	-		
of fusion (decomposition)	275-335		-	185	180		-	160-164		120-140	
GOST	13232-72		-	-	10215-72			-		-	

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[1] Volume swelling in water, 4.5-6%.

[2] GOST certified moisture content, 2%.

[3] GOST certified moisture content, 0.5%.

Table IV.37 cont.

Property	Fluorine-containing		Polyvinyl alcohol		Polyolefin				
	Polifen (teflon)	Ftorlon	Vinol	Modified	Polypropylene		Polyethylene		
							Low-pressure		
	Multi-filament	Monofilament	Multifilament		Monofilament and multi-filament	Staple	Monofilament and multifilament	Staple	High-pressure monofilament
Breaking strengths:									
kgf/mm²	33	40-130	60-100	120-130	29-65	33-49	30-60	21-34	8-25
g/tex	14.4	5-11	30	100	32-72	36-54	32-63	22-36	9-27
g/denier	1.6		3.3	11.1	-	-	-	-	3
Breaking length, km	15-20	18-60	26-40	85-100	-	30-70	-	-	
Density, g/cm³	2.2-2.3	2.16	1.26-1.3	1.32	0.91-0.92		-	-	-
Elongation at rupture, %:									
in wet state	-	-	-	-	15-50	20-40	10-45	70-110	20-80
in dry state	15-40	22-8	15-25	3-5					
Initial modulus of elasticity, kgf/mm² . 10⁻²	1	1.8-3.3	3-6	25-50	7.4	-	-	-	-
Moisture absorption (at φ 98%), %	0	8-15			-	-	-	<0.01	-
Thermal stability, °C	270	100-110	115	150	-	-	-	-	-
Heat capacity, cal/(g °C)	0.25	-	-	-	0.46		-	-	-
Thermal conductivity, cal/(m h °C)	0.14	-	-	-	0.08		-	-	-
Temperature, °C:									
of softening	326	132-136	200		140-165		90-127		-
of fusion (decomposition)	400	160	220-240		165-177	145-165	110-149		118-132
GOST	-	OST 6-06-4-70	-	-	TU 6-06-290-70; TU 6-06-301-70; TU 6-06-217-70; TU 6-06-327-71				

Table IV.38

Characteristics of synthetic fibers (heterochain polymers)

Property	Polyamide								
	Kapron (nylon 6)			Anid (nylon 66)			Enant (nylon 7)		
	Multifilament[1]	Cord filament	Staple[1]	Multifilament	Cord	Staple	Multifilament	Cord	Staple
Breaking strength:									
kgf/mm^2	40-62	74-85	41-62	45-64	62-90	40-62	44-52	82-87	43-50
g/tex	35-56	65-75	30-54	40-56	65-70	35-54	40-47	75-79	39-45
g/denier	3.9-6.1	7.2-8.3	3.3-5.6	4.4-5.5	6.1-7.7	3.8-5.0	4.4-5.2	8.3-8.8	4.3-5.0
Breaking length, km	40-50	55-70	-	40-50	55-70	-	40-47	75-78	-
Density, g/cm^3		1.14-1.15			1.14			1.10	
Elongation at rupture, %:									
in wet state	20-50	15-20	40-70	-	14-22	37-50	-	-	-
in dry state				25-40			24-26	15-17	50-65
Initial modulus of elasticity, kgf/mm$^2 \cdot 10^{-2}$	2.1-2.7	3.2-3.6		2.3-3.2	3.7-4.5		2.7-3.1	3.9-4.7	
Moisture absorption (at ϕ = 98%), %		7.0-8.0			6.8			2.6-2.8	
Volume swelling in water, %	10-12	9-11	-	8-12	9-11	-	-	-	-
Heat resistance, °C	-	60	-	-	60	-	-	60	-
Heat capacity, cal/(g °C)		0.35-0.36			0.34-0.345			0.452	
Thermal conductivity, cal/(m h °C)			0.21				-	-	-
Temperature, °C:									
of softening		170-200			235		-	-	-
of fusion (decomposition)		212-219			250-260			225	
GOST	7054-67 TU 6-06-285-70	15897-70 MRTU 6-06-245-69 OST 6-06-5-70	16008-70	-	-	-	-	-	-

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[1] GOST certified moisture content, 5%.

[2] GOST certified moisture content, 1%.

Table IV.38 cont.

Property	Polyamide		Polymethane		Polyester			
	Pelargone	Undecane	Spandex		Lavsan			Codel
	Multifilament		Multifilament and staple	Monofilament	Multifilament	Cord	Staple^2	Staple
Breaking strength								
kgf/mm^2	39-43	52-67	6.5-8.7	43-50	52-62	75-97	52-80	40-60
g/tex	37-41	51-63	5-8	36-41	40-45	58-72	38-60	29-42
g/denier	4.1-4.5	3.4-4.1	0.5-0.9	4-4.5	4.6-5.0	6.0-7.8	3.6-4.0	2.4-3.6
Breaking length, km	-	-	-	-	55-70	-	-	-
Density, g/cm^3	1.06	1.02	1.1	1.21		1.38-1.39		1.22
Elongation at rupture, %:								
in wet state	-	28-40		-	18-30			
in dry state	24-26		520-700	12-14		6-15	24-60	24-30
Initial modulus of elasticity, kgf/mm$^2 \cdot 10^{-2}$	3.5-4.2	2.8-3.2			9-10	10-12	2.5	
Moisture absorption (at ϕ = 98%), %	1.3	1.1-1.2	-	1-1.5		0.5-0.8		0.8
Volume swelling in water, %	-	-	-	-		3-5		-
Heat resistance, °C	-	-	150	-	-	150	-	-
Heat capacity, cal/(g °C)	0.487	0.51-0.58	-	-		32		-
Thermal conductivity, cal/(m h °C)	-	-	-	-		0.07		-
Temperature, °C:								
of softening	-	-	-	-		230-250		-
of fusion (decomposition)	185-205	176-180	250	183		250-260		290
GOST	-	-	-	-	10435-70 TU 6-06-326-71	TU 6-06-289-70	13231-67	-

Table IV.39

Commercial names of some polymer fibers

Country	Polymer material		
	Polyamides	Polyesters	Polyvinyl alcohol
USSR	Capron (polyamide 6, polycaprolactam)	Lavsan (polyethylene terephthalate)	Vinol
USA	Nylon 6, Caprolan, Nylenka, monosheer, Nylex	Dacron, fortrel, Enkalon, Algil, Amilor, Vicron, Vitel, Delvon, Codel, Fiberfill	-
England	Nylon 6, Luron, Cellon	Terylene, Flaflene	–
GDR	Dederon, Perlon, Wetrolon, Supron	Lanon	-
FGR	Perlon, Darlon, Crinex, Nefalon, Sanderit, Nylon 6, Rodialon, Fridon	Diolen, Trevira, Firalon	Synthofil
Holland	Enkalon, Akulon, Bifil, Volenka, Volinek, Cordecalon, Perelenka	Terlenka, Akulen	-
Italy	Lilion, Ortalion, Forlion, Helion, Delfion, Nopalon, Epion	Terifal	-
Poland	Polan, Stilon, Merinopolan	-	-
China	Shinlon	-	-
ARE	Mizrilon	-	-
Czechoslovakia	Silon, Chemlon	Sviflen	-
France	-	Tergal	Rodoviol
Switzerland	Grilon, Bodanil	-	-
Rumania	Relon	-	-
Japan	Amylan, Toray-nylon, Kure-nylon	Teforon, Grilen, Toray-Tetolon	Mulon, Nulon, Kanebian, Vinylon, Ivankumi, Cremona, Kuravilan, Kurslon
Mexico	Nicel	-	-
Hungary	Damulon, Denalon	-	-
Spain	Dian, Perlofil, Techron	-	-

Table IV.40 and Figs. IV.23-IV.26 show certain properties of this type of fibers. /315

The Soviet-made polymer Fenilon, the structure of which is analogous to the aromatic polyamide Nomex made by Dupont, is an aromatic polyamide, poly(m-phenyleneisophthalamide), obtained by polycondensation of isophthalyl dichloride emulsion with m-phenylenediamine

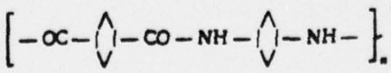

Table IV.40

Properties of fibers of high-temperature polymers

Property	Polymer								
	Nomex type polyamide	Polyiso-phthalyl hydrazide	Copolymer of iso- and tere-phthalyl hydrazides	Polyimide	Polybenzimi-dazole	Poly-1,3,4-oxadiazole	Aromatic staggered copoly-amides		Polybisthi-azolamide
							MMM-R	MMM-N	
Melting point, °C	400 (charring)	-	-	-	-	465	-	-	535
Breaking strength, g/denier at $\phi = 65\%$	5.5	5.2	6.0	6.9	4.9	5.3	6.0	6.3	7.8
Percentage elongation, % at $\phi = 65\%$	17	14	8	13	21	10	23	19	4
Modulus of elasticity, g/denier	-	115	151	78	115	216	101	94	168
Density, g/cm^3	1.38	1.44	1.45	-	-	-	1.36	1.35	-

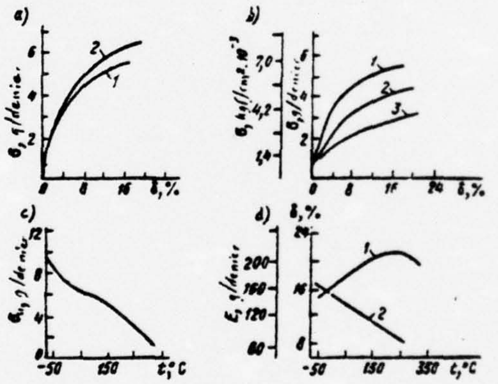

Fig. IV.23. Mechanical properties of monofils of heat-resistant polyamide "Nomex:" a - curves of stress σ vs elongation δ at 21°C and various deformation rates.

1 - 10% min; 2 - 150,000% min.

b - curves of stress σ vs elongation δ at different temperatures.

1 - 21°C; 2 - 177°C; 3 - 260°C.

c - breaking strength σ_u vs temperature; d - modulus of elasticity E (1) and elongation at rupture δ (2) vs temperature.

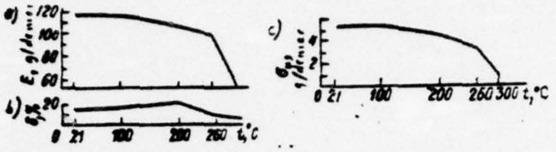

Fig. IV.24. Modulus of elasticity (a), percentage elongation (b) and breaking strength (c) of polyisophthalyl hydrazide fiber vs temperature

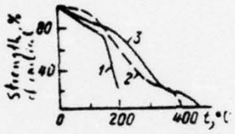

Fig. IV.25. Heat resistance of polyamide fibers
1 - nylon 6-6; 2 - "Nomex" NT-1 fiber; 3 - MMM-N-6 fiber

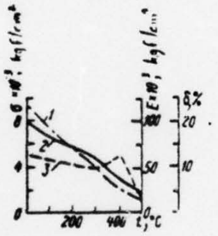

Fig. IV.26. Mechanical properties of polypyromellitimide fibers PM (with diphenyloxy groups in the chain) vs temperature
1 - strength; 2 - modulus of elasticity; 3 - elongation

To obtain fibers and electrical insulation paper with t_{work} 200-250°C and t_{stor} down to -70°C, the following brands of fenilon are produced by industry: VA (TY V-119-68); VB (TU V-120-68); fenilon solution (reaction syrup) (TY V-76-66). /317

The main physicomechanical properties of plastics obtained from fenilon are shown below.

ρ, g/cm^3	1.33-1.36
σ_u, kgf/cm^2	800-1200
σ_c, kgf/cm^2	up to 3200
a_1, kgf cm/cm^2	15-35
E_c, kgf/cm^2	up to 44,000

HB, kgf/mm^2	up to 34
t_u, °C	270
t_{glass}, °C	-280
Cold resistance, °C	-70

Other properties of fenilon are given below in Tables IV.41-IV.44.

Table IV.41

Mechanical strength of fenilon at different temperatures

Property	at t, °C					
	−70	−60	+20	+120	+200	+250
σ_u, kgf/cm^2	1270	1250	1030	818	630	630
δ, %	5,0	5,0	5,0	5,8	5,0	6,6

Table IV.42

Thermophysical characteristics of fenilon

Property	at t, °C				
	20	50	100	150	200
λ, kcal/(m h °C)	0,16	0,17	0,20	0,22	0,24
Temperature conductivity, $a \cdot 10^4$, m^2/h	3.7	3.4	3.4	3.2	3.2
c_{sp}, kcal/kg °C	0,34	0,39	0,46	0,52	0,58

Table IV.43

Electrical properties of fenilon

Conditions of measurement	ρ_v, ohm cm	ρ_s, ohm	U_{lim}, kV/mm
20° C	2×10^{14}	2×10^{13}	65
20° C (98%, at 40° C (48 h)	3×10^{13}	2×10^{13}	—
200° C	2×10^{14}	2×10^{13}	22
250° C	6×10^{12}	2×10^{13}	19

Table IV.44

Coefficient of thermal linear expansion of fenilon at different temperatures

Temperature, °C	$\alpha \cdot 10^6$ deg	Temperature, °C	$\alpha \cdot 10^6$ deg
196 : 190	39.8	−130 + 90	38.9
190 : 180	60.4	90 ÷ 30	30.2
180 : 170	99.3	− 30 ÷ 0	34.5
−170 + − 160	77.7	0 + 30	34.5
− 160 + − 150	51.8	30 + 150	38.9
−150 ÷ −140	43.2	150 + 220	34.5
−140 ÷ −130	43.2	220 + 250	25.9

14. Inorganic Fibers /319

Fibers obtained from inorganic materials, including metallic ones, have a number of valuable properties and find wide application in modern technology, including shipbuilding. They are of major interest as the base of composite materials with special properties.

The material for such fibers may be metals and alloys; pure elements (C, B); oxides (SiO_2); glasses of various compositions; graphite; ceramics; crystallizing silicates (slags, rocks), etc.

Many of these materials, which have valuable properties and are widely used, have been discussed in the literature.[12,15,26]

We will briefly discuss some representatives of this group.

A. Polycrystalline inorganic (ceramic) fibers

Fine polycrystalline fibers of various inorganic materials have the structure of well-fired pore-free ceramic with nonoriented grains and consist of crystallites whose dimensions are much smaller than the cross section of the fiber. Polycrystalline inorganic fibers occupy an intermediate position between "whiskers," on the one hand, and metallic and glass fibers on the other. They may be both continuous and stable fibers; in dimensions, they resemble textile fibers and can processed into yarn. The usual methods of preparation of such fibers include molding by extrusion from suspensions or colloidal solutions, and less frequently, free casting as film followed by drying and drawing of the film into fibers.

In any fabrication variant, the dried fibers are fired at a high temperature (>>1000°C) to form the necessary compounds and obtain the specified properties. The materials used for the fibers may be metal oxides and their solid solutions (Al_2O_3, $Al_2O_3 \cdot Li_2O$, ZrO_2, etc.); silicates ($ZrSiO_4$); nitrides (BN) and many others. In the USA, fibers are produced from aluminum silicate (under the name "fiberfrax") by atomizing the melt on a rapidly rotating disk. Average characteristic of long fibers: length - 50-75 mm (fluctuations, 13-254 mm) with a diameter of about 4 μm; length of short fibers, up to 3.8 mm; mean diameter, 2.5 μm (flucutations up to 10 μm).

Density of fiber material, 2.73 g/cm^3; MP > 1760°C; t_{work}, up to 1260°C. Composition of long fibers, %: 51 Al_2O_3, 45 SiO_2, 3.4 ZrO_2; short fibers, %: 51 Al_2O_3, 47 SiO_2, 0.7 B_2O_3, 0.7 Na_2O. The thermal conductivity of the long-fibered material (ρ = 96 kg/m^3) is as follows:

t, °C	320	540	760	870	980	1090
λ, cal/(cm sec deg)	0,20	0,41	0,68	0,86	1,03	1,16

In addition to being used directly, fiberfrax fibers are used as starting material in the manufacture of heat resistant and refractory felt, mats, paper, textile articles, rope articles, coverings, molding mixtures, etc., and also as reinforcing materials. /320

Similar in composition to the one discussed is fiber obtained from kaolin ($Al_2O_3 \cdot 2SiO_2$) melts (called kaolin fiber in the USSR and *Kaowool* in the USA). The fiber is obtained in the form of a felt and staple up to 200 mm long with a diameter of 1-3 μm. The density of the material is 2.6 g/cm^3, MP = 1750°C, t_{work} = 1260°C (for brief periods) and 1100°C (for long periods). The thermal conductivity of kaolin fiber of different densities is shown in Table IV.45.

Table IV.45

Thermal conductivity of kaolin fiber

Average temperature, °C	Thermal conductivity λ·10^3, cal/(cm sec deg), at apparent density, kg/m^3		
	48	96	160
200	0,17	0,15	0,13
320	0,27	0,23	0,17
430	0,39	0,32	0,22
540	0,54	0,14	0,28

Kyanite ($3Al_2O_3 \cdot 2SiO_2$) fibers of brands J-M are obtained in the USA from melts of mixtures *of siliceous aluminosilicates* (kyanite, sillimanite, andalusite) with Al_2O_3 or mullite. The fiber diameter is 1-5 μm (average, 3 μm); the apparent density of the felt is 65 kg/m^3; t_{work}, up to 1100°C. The thermal conductivity of the fibers is shown in Table IV.46.

J-M fibers are used as the base for felts (thermoflex and kerafelt) and J-M fiber mass (kerafiber). They are used for high-temperature filters, high-temperature insulation, etc.

Also well-known are continuous ceramic fibers obtained from refractory aluminosilicate glasses; aluminum-barium glasses with exothermic additions; bauxites, boron /321
nitride; borocalcium silicates.

The group under consideration includes potassium titanite ($K_2Ti_6O_3$) fibers produced in the USA under the brand name Tipersol. The mean fiber diameter is 1 μm.

Table IV.46

Thermal conductivity of kyanite fibers

Average temperature, °C	Thermal conductivity λ·10³, cal/(cm sec deg), at apparent density, kg/m³			
	48	96	192	288
160	0.13	0.12	0.11	0.11
320	0.23	0.18	0.16	0.15
430	0.31	0.24	0.21	0.18
540	0.43	0.30	0.26	0.22

the length is 0.2 mm, and in some cases 20-30 mm; ρ = 3.6 g/cm³; MP = 1371°C; c_{sp} = 0.22 cal/(g deg); H_{Mohs} = 4.0; σ_u = 16.3 kgf/mm²; δ = 0.59%; E_{tens} = $2.8 \cdot 10^3$ kgf/cm². The thermal conductivity for batches of different densities is shown in Fig. IV.27.

Polycrystalline fibers are made from zirconium dioxide stabilized with 5% CaO. The fiber length is 5-51 mm; diameter, 2.5-12.5 μm; density, 5.9 g/cm³; MP ~2590°C; σ_u, up to 38 kgf/mm²; t_{work} > 1650°C.

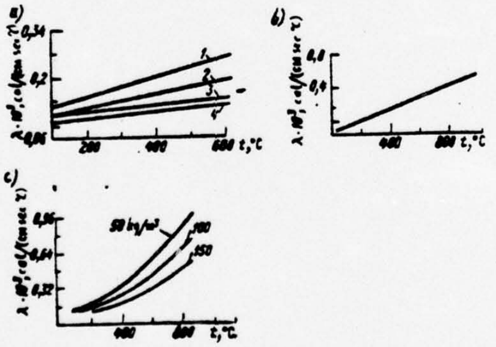

Fig. IV.27. Thermal conductivity of certain inorganic fibers: a - fibrous material based on potassium titanate.
1-4 - materials of different densities (according to the degree of its increase): b - "Microquartz J-M" fibers, ρ = 0.048 g/cm³; c - felt of Refrazil fiber. Numbers on curves - values of ρ, kg/m³.

B. Materials from quartz fiber

Quartz fiber - one of the forms of high-temperature fibers used in modern technology - is of particular interest, since it has valuable physicochemical properties: a high electrical resistance, high melting point and heat resistance, low coefficient of thermal expansion, and high chemical stability.

Materials of quartz fiber may be used at high temperatures and pressures, high velocities, and also in corrosive media.

The melting point (MP) of quartz fiber is in the 1720–2200°C range. The viscosity is preserved in the $10^{7.5}$–10^5 P range.

In long-term operation, materials from quartz fiber are stable up to 1200°C. /322
Sintering of the fibers (deformation in the solid phase) without softening takes place at 1450°C.

The thermal conductivity coefficient of quartz fiber and quartz wool at room temperature is 0.03 kcal/(m h deg). As the temperature rises to 1000°C, the thermal conductivity coefficient increases to 0.2 kcal/(m h deg).

In comparison with massive quartz glass, fine quartz fibers have a high mechanical strength. Thus, the tensile strength of quartz fibers is over 30 times greater than that of massive quartz glass.

As a result of phase transformations at high temperatures, associated with a change in volume, quartz fiber undergoes shrinkage. This must be considered when using quartz materials.

Quartz fiber is resistant to water, high-pressure steam, various acids, and other chemical reagents. Organic and mineral acids of any concentrations leave quartz fiber almost unaffected. The only exceptions are hydrofluoric and phosphoric acids (the latter attacks quartz fiber above 300°C).

Quartz fiber is one of the best dielectrics; it is characterized by a low electrical conductivity even at high temperatures and low dielectric losses over a wide frequency range. At room temperature, the volume electrical resistivity ρ_v of quartz fiber is 10^{17}–10^{18} ohm cm.

Fibrous electrical insulation materials of quartz fiber are water-resistant, and their surface resistance ρ_s does not exceed 10^{12} ohm as the humidity increases.

The permittivity and dielectric loss tangent of articles made of quartz fiber remain practically unchanged as the temperature is raised to 700°C.

Given below are the basic properties of quartz glass, from which quartz fiber is made.

SiO_2 content, %	99.9
Density ρ at 20°C, g/cm^3	2.203
Melting point, °C	1720
Boiling point, °C	2300
Viscosity in the 1720–2200°C temperature range, P	$10^{7.5}$–10^5
Guaranteed temperature range of use, °C:	
in long-term operation	−250 to +1200
in short-term exposure to heat	−250 to +2000
Coefficient of thermal expansion α in the 0–1000°C temperature range, deg^{-1}	$0.54 \cdot 10^{-6}$
Mean specific heat capacity c_{sp} in the 20–650°C range, cal/(g deg)	0.23 /323
Dielectric loss tangent at a frequency of 10^6 Hz $\tan \delta_{10^6}$ at 0–700°C	$1.5 \cdot 10^{-4}$

Permittivity at 10^6 Hz ε_{10^6} at 0-700 °C	3-4
Modulus of elasticity E_Y at 20°C, kgf/mm^2	7450

Articles of quartz fiber with an organosilicon lubricant are equivalent in mechanical properties to materials based on industrially produced aluminoborosilicate fibers.

Quartz wool, felt, mats and fabrics are excellent heat-insulating materials.

Twisted quartz fibers of different numbers (from 5 to 110) are being produced. Quartz fabrics are made in a wide assortment of thicknesses, from 0.1 to 1.0 mm. The warp and weft strengths of the fabric are different. Thus, for satin quartz fabric 0.69 mm thick, the warp breaking stress is 210.4 kgf, and the weft breaking strength is 204.0 kgf.

Quartz paper and thin quartz fabrics are good insulating supports and can be used in electronics.

Twisted quartz fibers and ribbons can be successfully used for insulating the conductors of electrical machines and power cables operating under high humidity conditions and in corrosive media.

Quartz fiber fabrics are useful in filtering hot acid solutions as well as gases and for separating precipitates and sludge.

Particles of quartz fiber combined with mineral binders and organosilicon, phenol-formaldehyde and epoxy resins may be used as high-temperature fillers for structural and heat-insulating plastics.

Quartz fibers made of SiO_2 melts are produced abroad in a wide assortment. Typical properties of fibers of such materials are as follows: $\rho = 2.20\ g/cm^3$; $E = 7030\ kgf/cm^2$; α_m (0-300°C) $= 0.55 \cdot 10^{-6}$; $t_{soft} = 1667°C$; $t_{work} = 1070°C$; $\varepsilon_{10^6} = 3.78$; $\tan \delta_{10^6} = 0.0009$; $\lambda \cdot 10^3 = 3.3$ cal/(cm sec °C); $c_{sp} = 0.165$ cal/(g °C).

C. Silica fiber

One of the promising inorganic man-made materials are silica fibers. They are obtained by chemical treatment (with acid) of glass fibers from glasses of definite composition while low-melting oxides dissolve and almost pure silica remains).

Depending on the initial glass composition, one can obtain silica fiber containing up to 98% SiO_2 (in terms of the calcined substance) or silica fiber with additions of high-melting oxides. In contrast to quartz fibers, silica fibers contain about 1-2% of impurities, due to the technological circumstances of their /324
production.

Silica materials are obtained from glass No. 11 and 151.

Silica fiber has a high temperature stability. Its melting point is around 1600-1650°C. The maximum temperature of application of silica fiber in prolonged operation is 1000-1200°C, i.e., 500-600°C higher than the temperature of application of fiber made of alkali-free aluminoborosilicate glass.

Silica fiber is microporous and in the air-dried state contains 11-14% water, which may be partially or completely removed by calcining. A practically complete dehydration takes place at 600-700°C.

The breaking strength of silica fiber is around 80 kgf/mm^2. As the temperature rises, the strength decreases continuously, and is 0 above 1100°C. The shrinkage at 600-800°C is 5-6%.

To obtain "shrinkage-free" silica fabrics, they must be heated for 5-30 min at 600°C (depending on the thickness).

Silica fiber has a high chemical resistance to neutral and acid media at high temperatures. Silica fiber made of glass No. 151 is more stable to alkaline /325
media than silica fiber made of glass No. 11.

The physicochemical properties of silica fabrics are chiefly determined by the physicochemical properties of silica fiber.

At the present time, woven and nonwoven silica fabrics are produced by industry. Woven fabrics include fabrics of twisted filaments, strand fabrics made of twisted filaments, as well as bands of different widths.

Silica fabrics of different thicknesses - from 0.2 to 1.0 mm - are made from primary filament of metric numbers 75-85 with a 5-7 μm fiber diameter. The fabrics are made with a special lubricant, and the sintering temperature in a short-time test (30 sec) is 1350-1400°C.

Table IV.47 shows the properties of industrially produced woven silica fabrics.

Table IV.47

Properties of woven silica fabrics

Brand of fabric (ribbon)	Filaments		Width, cm	Thickness, mm	Weight of 1 m^2 of fabric, kg, not more than	Density - number of filaments per cm		Breaking stress (strip 25x100 mm), kgf, not less than		Content of lubricant, %, not more than
	Number	Number of ends				Warp	Weft	Warp	Weft	
KT-11-3,0,2	10±1	8	88±3	0.20±0.03	200	10±1	10±1	25	25	1.0
KT-11	5±1	16	88±3	0.35±0.05	350	9±1	8±1	40	40	0.8
KZh-11-2	0.5	160	88±3	about 1.0	1100	2	3	30	30	1.0
KTsZh-151-2	0.5	160	88±3	about 1.0	1100	2	3	30	30	1.0
KL-11	10	8	1.5±0.2	0.30±0.05	5±1 lin.m	18±1*	10±1	30*	—	—

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*For the entire width of the ribbon.

Silica fabrics are made of high-temperature insulation material used for manufacturing special purpose glass-reinforced plastics, electrical insulation glass fabric laminate, used under ordinary conditions and under increased relative humidity and air temperature conditions. In addition, they can be used for filtering corrosive solutions, melts, air and gases at high temperatures.

Nonwoven silica materials include filament, fiber, board, as well as molded articles of complex configuration.

Silica filament of low metric numbers (10, 5, 3) is made from filament of numbers 75-85 with a fiber diameter of 5-7 μm and a special lubricant. The filament twist is 150 twists/m in this case.

Silica filament is used as a reinforcing material for strengthening plastics, sewing mats, and making combined woven materials.

Silica fiber is produced in the form of a wool consisting of random fibers 5-7 μm in diameter. The fiber must meet the following requirements:

Density of loose fiber, kg/m^3	100
Melting point, PC	1650
Application temperature limits during prolonged operation, °C	-60 to +1100
Thermal conductivity coefficient, kcal/(m h deg):	
at an average temperature of 160°C	0.055
at an average temperature of 460°C	0.120

Silica fiber is used as a heat-insulating material at high temperatures and can also serve as a semifinished product in the manufacture of molded silica articles.

Silica fibers with a high SiO_2 content, obtained by leaching glass fibers, constitute a material that is widely used abroad. For example, Refrazil fiber is obtained by leaching fiber glass with hydrochloric acid. The diameter of /326
Refrazil fibers is 0.8-12 μm, the SiO_2 content is 96-99%, and MP > 1650°C. The thermal conductivity is shown in Fig. IV.27 c. Refrazil retains its electrical insulating properties up to 1000°C. The material is used as a wool, fabric, ribbon, felt, braiding, rope articles, coverings, and reinforcement for plastics. The name Microquartz J-M in the USA stands for thin fibers and felt containing more than 99% SiO_2; fiber diameter, 1.3 μm; MP > 1600°C. The thermal conductivity of this material is shown in Fig. IV.27 b.

D. Elemental fibers

Boron fibers. Fibers made of pure boron B are the latest and very promising materials. They are of particular interest as a reinforcing filler for high-strength and high-modulus composites - boron plastics.

Modern boron fiber is characterized by the following properties: $\rho = 2.6$ g/cm^3 (including a W core); $E = 39$-$42{,}000$ kgf/mm^2; $\alpha \cdot 10^6 = 1.5$/deg; $\sigma_u = 350$ kgf/mm^2; MP = 2050°C; $H_{Mohs} > 9$; Poisson's ratio, 0.21; rigidity modulus, 17,900 kgf/mm^2. Attention is drawn to the great hardness of the material and its modulus of elasticity, which is five times as high as that of fiber glass. At the present time, the chief method of fabrication of boron fibers consists in the deposition of boron, which takes place as a result of thermal decomposition of vapors of its compounds when they come in contact with a substrate heated to a high temperature. The decomposing compounds used are primarily volatile boron halides (of the general formula BX_3, where X is Cl and Br) or boron hydride (for example, B_2H_6). The refractory heated substrate used is a thin (~13 μm) tungsten wire heated by electric current to the required temperature (~1000-1200°C for BCl_3-H_2 mixtures).

During the deposition, the tungsten core reacts with the depositing boron, forming tungsten borides (WB_4, W_2B_5). When the wire thickness is ~13 μm, this requires 30-55 sec.

The diameter of the boron fiber obtained from BCl_3 after 1-2 min of exposure in the deposition chamber ranges from 76 to 137 μm.

The continuous fiber length is 3000 m. The structure of the tungsten wire surface affects the structure of the depositing boron. Etching of the boron fiber surface makes it possible to increase its tensile strength, and the bending strength increases much more abruptly (to 1300-1400 kgf/cm^2).

Carbon fiber (C fiber). Carbon fibers is the term applied to fibers consisting almost completely of pure carbon.

Fibers containing 91-98% C are classified as carbon fibers, and those containing more than 98% C, graphite fibers. The starting materials in the manufacture of C fibers are infusible polymers in the form of fibers, converted by solid phase pyrolysis (by heating at 1000°C, then graphitizing at 2000-3000°C) into /327
carbon fibers. At the present time, polyacrylonitrile and *cellulose (viscose)* fibers are most widely used for this purpose.

Carbon fibers are characterized by a low specific mass, a high rigidity, a substantial tensile strength, but a low interlaminar shear resistance (5-6 kgf/mm^2). C fibers must retain their mechanical strength up to 2000°C. C fibers conduct electricity and heat: λ along the fiber is 40 kcal/(m h °C); ρ_{sp} is about 3 ohm mm^2 m^{-1}; α up to 1000°C is in the range of $1.5 \cdot 10^{-6}$ deg^{-1}, and at room temperature has a negative value ($-1 \cdot 10^6$ deg^{-1}), passing through zero in the 200-400°C range. Cellulose-base C fibers acquire a high strength only after heat treatment. Polyacrylonitrile C fibers require no treatment. All the properties of C fibers of different batches vary over relatively wide limits (26-30% for σ_u, 9-11% for E, 6-8% for the diameter). Table IV.48 gives the average values of the basic properties of C fibers.

The diameter of the fibers ranges from 5 to 50 μm.

A characteristic feature of carbon and graphite fibers is a high heat resistance, infusibility, chemical inertness, and low specific density (for carbon fiber, $\rho \sim 1.7$ g/cm^3; for graphite fiber, ~2.0 g/cm^2).

Disadvantages include a comparatively high thermal conductivity and low mechanical properties (σ_u of carbon fibers is 60-90 kgf/mm^2; graphite fibers, 40-50 kgf/mm^2).

Randomly intertwined graphite and carbon fibers form corresponding felts, which have valuable properties.

Graphite felts are obtained at temperatures up to 2700°C, they contain practically no volatile products, and carbon felts are obtained by heating at 800°C and contain up to 8% of volatile compounds. The specific surface of graphite felts is ~3 m^2/g and the resistance is 0.3-0.9 ohm/□, and that of carbon felts, about 150 m^2/g and 500 ohm ~ 1 Mohm/□. Accordingly, carbon felts are frequently regarded as low-activity forms of activated carbon.

Table IV.48

Basic properties of some carbon fibers produced by foreign firms

Brand	γ, g/cm^3	σ_u, kgf/mm^2	σ_{sh}, kgf/mm^2	$E \cdot 10^{-4}$, kgf/cm^2	Breaking length, km	Specific E modulus, km$\cdot 10^{-3}$	Filament diameter, µm
UCC Tornel 25	—	125	—	1,75	86	12	—
Tornel 50	1,63	180	—	3,50	112	22	—
Courtaulds Type A	1,8	190—230	$\frac{6,2-7,0^*}{-}$	2,0—2,3	103—124	10,8—12,4	7,5—8,0
Type HM**	1,94	180—210	$\frac{2,3-3,3}{5,6-7,1}$	3,5—4,2	92—108	18—21,9	7,0—7,5
Type HT**	1,85	230—260	$\frac{4,4-5,5}{7,4}$	2,4—2,8	121—137	13,2—14,7	7,5
Morganite Type I (HM)	2	140—210	$\frac{-}{5,6}$	3,8—4,4	70—105	19—22,5	7,5± 0,5
Type II (HT)	1,75	245—315	$\frac{-}{7,7}$	2,45—3,15	129—165	12,9—16,5	8,0± 0,1
Sigraphil HF**		220—250	—	2,0—2,5	120—140	11,5—13,5	—

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* Numerator - without processing; denominator - with processing.

** HT, HF - high-strength; HM - high-modulus.

Table IV.49

Some properties of graphite and carbon felts

Property	Graphite felt				Carbon felt			
	WDD	WDF	WDH*	WDK*	WDC	WDE	WDC*	WDJ*
Initial width, mm	812	812	812	812	900	900	900	900
Mass of 1 m^2, g	182	358	362	784	172	476	355	767
Thickness, mm	1,7	5	2,5	6,5	1,7	6,5	22,9	6,7
Apparent density, kg/m^3	113	80	172	159	107	87	165	118
Strength, kgf/cm, strip width:								
in longitudinal direction	0,108	0,270	1,96	1,8	0,18	0,54	1,98	1,44
in transverse direction	0,054	0,18	1,96	1,96	0,09	0,54	1,08	0,54
Electrical resistance, ohm:								
in longitudinal direction	0,6	0,5	0,4	0,3	Several megohms per square			
in transverse direction	0,9	0,9	0,5	0,3				
Permeability to vapor, m^3/min m^2:								
at P = 0.5 mm H_2O	40,5	18,0	10,5	7,5	—	—	—	—
at P = 12 mm H_2O	—	—	—	—	39	19,5	10,5	9,0

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* Fabric-reinforced material.

Some characteristics of these materials are given in Table IV.49.

Graphite yarn WVC, produced in the USA (Union Carbide Corp.), is formed by twisting two filaments in 1.5 turns over a length of 25.4 mm. Each filament consists of 720 graphite fibers of brand Thornel 50TM. The main properties of the fibers are: σ_u (for a length of 25.4 mm) = 20,000 kgf/cm^2; δ = 0.6%; $E_Y = 3.5 \cdot 10^6$ kgf/cm^2; ρ = 1.63 g/cm^3.

The properties of the yarn (different batches) are σ_u = 21,000 and 16,400 kgf/cm^2; $E_Y = 3.8 \cdot 10^6$ and $3.4 \cdot 10^6$ kgf/cm^2. When WVC-130 yarn was used in the amount of 50-60 vol.% for making a composite material with an epoxy binder (mixture of 100 parts by weight of EBL-2256 resin of low viscosity with 27 parts by weight of aromatic amines), the following characteristics of the solidified material were /329 obtained: σ_u = 6100-8350 kgf/cm^2; $E_Y = 1.49 \cdot 10^6 - 1.81 \cdot 10^6$ kgf/cm^2; $E_{b\ \mathrm{stat}} = 1.47 \cdot 10^6 - 1.78 \cdot 10^6$ kgf/cm^2; $E_{b\ \mathrm{dyname}} = 1.5 \cdot 10^6 - 1.53 \cdot 10^6$ kgf/cm^2; σ_b = 7400-8780 kgf/cm^2; $E_b = (1.57\text{-}1.88) \cdot 10^6$ kgf/cm^2; $E_{\mathrm{twist\ dyname}} = (0.463\text{-}0.610) \cdot 10^5$ kgf/cm^2.

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