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RADIO-TRANSPARENT CERAMICS: YESTERDAY, TODAY, TOMORROW

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The physico-technical properties and features of production of several radio-transparent ceramics are examined in connection with the tactical-technical characteristics of modern missile weaponry. It is convincingly shown that no single material can satisfy all of the requirements which missile radomes must meet under varying service conditions. An attempt is made to determine the levels that radome materials' property indices must reach and to identify the technological, materials-science, and design problems that need to be addressed in order to significantly improve the tactical-technical characteristics of different missile systems.

Keywords: radio-transparent materials, quartz ceramics, sitalls, glass-ceramics, radome.

Scientific and technical progress in the 19th Century and the beginning of the 20th Century was characterized by the intersection of many different spheres of activity, including aviation. New types of aircraft were invented that were oriented toward military applications: surveillance, combat However, the maximum flight speeds and altitudes of the airplanes were low and made the planes vulnerable to ground-based weapons: rifles and machine guns.

The subsequent invention of more modern aircraft (with higher maximum speeds and altitudes and greater maneuverability) made it necessary to develop more modern armaments to combat them in military conflicts. The new airplanes were equipped with cannons and machine guns for air combat, anti-aircraft guns were invented for ground use, and systems were developed to detect approaching airborne targets and provide sufficient warning of possible air attacks. An extensive air-defense system was created.

The middle of the last century was marked by the addition of jet airplanes to the military arsenal of several countries. On the one hand, the maximum speeds of these planes (800 – 900 km/h) made them significantly less vulnerable to conventional anti-aircraft weapons. On the other hand, the reaction times of the pilots were now clearly too slow to allow them to make effective use of on-board cannons and machine guns.

Thus, the trends in aviation technology were clearly pointing to a need to develop efficient means of detecting and destroying enemy airplanes as quickly as possible. Attempts to meet this need led to the invention of various types of missiles: air-to-air missiles, installed on board airplanes and designed to destroy targets in flight; air-to-surface missiles, also on board airplanes and designed to destroy targets on the ground and on water; surface-to-air missiles, installed in mobile launch containers or on open mobile or stationary platforms and designed to destroy airplanes and missiles at long range. Parallel with the developments in missile technology, work was being done on inventing precision-guidance systems that could accurately lead missiles to their target regardless of the weather conditions or the location of the launch site.

One of the most important parts of modern radar-guided missiles is the antenna housing. The main antenna housing not only protects the antenna block from climatic and aerodynamic factors but also actually determines a missile's tactical-technical characteristics (TTCs). It does so because it determines the missile's aerodynamic performance, determines the precision with which the missile is guided to the target, and withstands the main thermal and mechanical loads on the missile during maneuvers. The requirements on the housing (radome) and its constituent material have become more demanding as missiles' speeds and maneuverability have increased. For different classes of missiles moving at speeds in the range 5 – 12 M, the temperature on the surface of the radome can reach 2000°C and the mechanical loads can increase to 10 tons. The glass-fiber-reinforced plastics that were used to make the antenna housings of the

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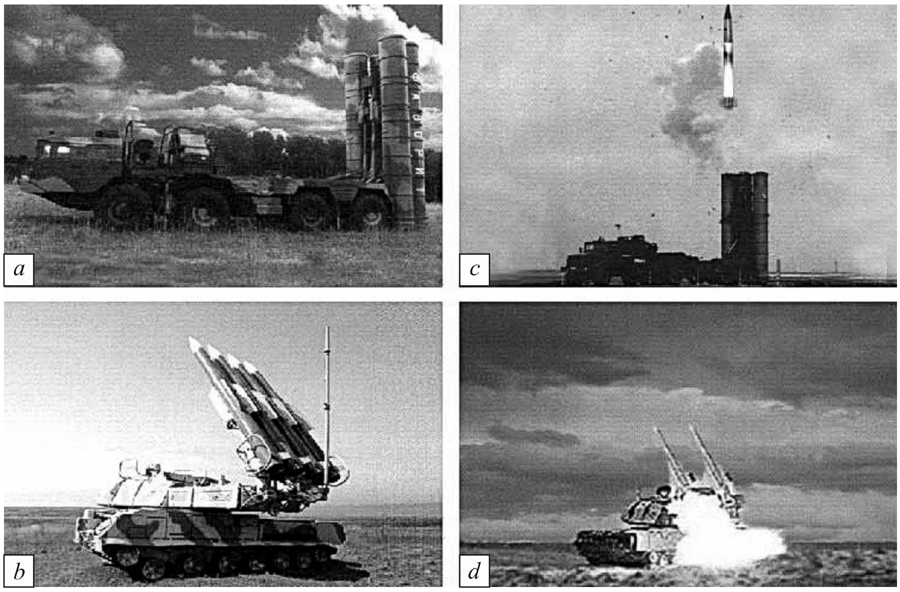

Fig. 1. Examples of modern missile complexes and missiles equipped with antenna housings made of radio-transparent materials: *a*) anti-aircraft missile complex (AMC) S-300; *b*) AMC BUK; *c*) launch of quartz-radome-equipped 48H63 missiles from AMC S-300; *d*) launch of sitall-radome-equipped 9M317 missiles from AMC BUK.

first missiles no longer satisfy present-day requirements due to their inadequate refractoriness.

During the 1960s, the U. S. and the USSR both began working on the development of ceramic materials for the radomes of high-speed missiles. A wide range of materials was used: ceramics based on oxides of silica, aluminum, magnesium, beryllium, and other elements, nitride ceramics, and sitalls — glassy-crystalline materials based on glass. Progress in this field has now reached the stage where three types of materials are in common use: sitalls, high-alumina ceramics, and quartz ceramics. The high-alumina ceramics are used to make the radomes of air-to-air missiles that operate at speeds in the range 4 – 4.5 M. Such materials are especially widely used in the U. S. for the radomes of "Sparrow" missiles [1].

TABLE 1. **Tactical-Technical Characteristics of Airplanes and Potential Missile Carriers**

Country	Model of airplane	Type of airplane	Characteristics of the airplane				
			maximum speed, km/h, at the altitude		range	length, m	
			>10 km	<3 km		take-off run	landing run
Russia	MiG-23ML	Tactical fighter	2500	1350	—	500	750
	MiG-29-9B	The same	2400	1500	680	240	600
	MiG-31	Fighter-interceptor	3000	1500	2200	1200	800
	SU-30	The same	2450	1300	250	550	670
U. S.	F-111	Multipurpose attack plane	2650	1470	2400	—	—
	F-16	Multipurpose fighter	2140	1470	925	—	—
	F-22A Lockheed	The same	2335	—	1285	—	—
	Phantom	The same	2300	1460	1270	—	—
France	Mirage 1	Multipurpose fighter- bomber	2350	1470	900	—	—
	Mirage 2000	Fighter-bomber	2330	100	1480	—	—
	Rafale	Multipurpose fighter	2100	1390	1000	300	400
England	Harrier	—	—	1200	500	—	—
	Hawk-2000	Ground attack plane	—	1020	1200	—	—
China	J-7	Fighter	2150	—	1300	900	800
	J-8	The same	2330	—	1000	670	1000
Israel	KFIRS-7	Multipurpose fighter	2440	1370	1185	—	—
Italy	Fiat E-91	Reconnaissance-attack fighter	2025	1130	600	—	—
Sweden	Viggen	Fighter-bomber	2125	1470	>1000	—	—
FRG + England + Italy	Gripen	Multipurpose fighter	2550	1470	—	—	—
	Tornado	Multi-purpose airplane	2300	1480	1900	—	—
	Jaguar	Fighter-bomber	1700	1320	1400	—	—

High-alumina ceramics are generally not used in Russia to make radomes for reasons that will be explained below.

Sitalls (Pyroceram-9606, Pyroceram-9608, AS-418, AS-370, etc.) are used both in Russia and the U. S. to make radomes for ground-to-air and air-to-air missiles operating at speeds of 4 – 7 M. Sitalls have been used in particular to make ship- and aerodrome-based missiles. Due to the absence of porosity, these materials exhibit exceptional long-term resistance to the effects of seawater, dust, and high concentrations of moisture even when they are painted [1].

Quartz ceramics have found wide use in Russia and abroad in the production of different classes of high-speed missiles operating at speeds of 5 – 10 M [1 – 3].

An analysis of the TTCs of modern military aircraft and missiles in the most developed nations of the world [2 – 5] shows that nearly all of these countries have airplanes that could carry missiles and that have similar characteristics (Table 1). Accordingly, it follows from the data in Table 2 that there are no substantial differences between the missiles of the different nations in terms of the characteristics shown in this table. Given this circumstance, it is possible to take a general approach to examining the properties of radome materials for missiles of different classes. Figure 1 shows some examples of modern missile complexes equipped with radomes made of inorganic radio-transparent materials.

For high-speed missiles, the most important requirement that must be satisfied by the material of the radome is undoubtedly *refractoriness.* In this sense, high-alumina ceramics have a clear advantage. The temperature at which the state of aggregation of such ceramics changes is 2050°C, while it is 1200 – 1350°C for sitalls and no higher than 1300°c for ceramics based on quartz glass. However, under conditions that subject the radome to brief heating on one side - which actually takes place during the use of a radome - the performance of the product is determined by other factors.

For inorganic materials, the most important of those factors is *thermal resistance* (resistance to thermal shock and cyclic thermal loading). The experimental criterion most commonly used to evaluate this property is the largest tem-

TABLE 2. **Tactical-Technical Characteristics of Radar-Guided Missiles**

Air-to-Air Missiles

Indices	Russia			U. S.			England	France
	Kh-15	Kh-22	Kh-58	AGM-129 A	Shrike	Harm	Alarm	Armat
Flight speed, m/sec	1800	100	1300	250	1000	820	800	830
Range of fire, km	<300	<550	<120	<300	<50	<80	<70	<150
Type of carrier	Tu-95MS, Tu-22MZ, Tu-160, Su-27K, Su-27IV	Tu-22K, Tu-95 K-22, Tu-22M2, Tu-22MZ	Su-17 MZ, Su-17 MU, Su-24, Su-24 M, MiG-25BM	B-52, B-1, B-2	F-4, F-105, A-6	Air force, Navy	Tornado	Jaguar, Mirage, Rafale

Air-to-surface missiles

Indices	Russia			U. S. ("Sparrow")				England	France	Italy
	RVV-AE	R-27 R	R-33 R	AAM-N-2	AlM-7E	AlM-7F	AlM-7M	Skyflash	Matra Super	Askand-7A
Flight speed, m/sec	1450	1250	1250	700	1000	1120	1120	1450	750	1100
Range of fire, km	100	<130	<80	8.0	25	70	100	50	18	50
Type of carrier	Su-27, MiG-29	MiG-29K, MiG-29M, Su-27, Su-27K	MiG-23M, MiG-23MR, MiG- 23MLD	F-4, F-8, F-14	F-8, F-14, F-111	F-4, F-8, F-14, F-111	F-4, F-8, F-14, F-111	F-4, Tornado	Mirage, F-104, Starfire	F-104 S

Surface-to-air missiles

Indices	Russia					U. S.
	AMC S-300V	AMC S-300 PMU	AMC S-300 PMU 1	AMC BUK	AMC ShTIL'	Patriot ground rocket
Flight speed, m/sec	1700	2100	2400	1230	1230	1600
Maximum range, km	400	90	400	—	—	60
Target-altitude range, m	25 – 30000	25 – 25000	10 – 25000	15 – 25000	15 – 25000	60 – 24000
Target-speed range, m/sec	≤3000	≤2255	≤6450	≤1200	≤1200	≤1800
Mobility	Self-propelled	Self-propelled	Self-propelled	Self-propelled	Ship-based	Transportable (by vehicle)

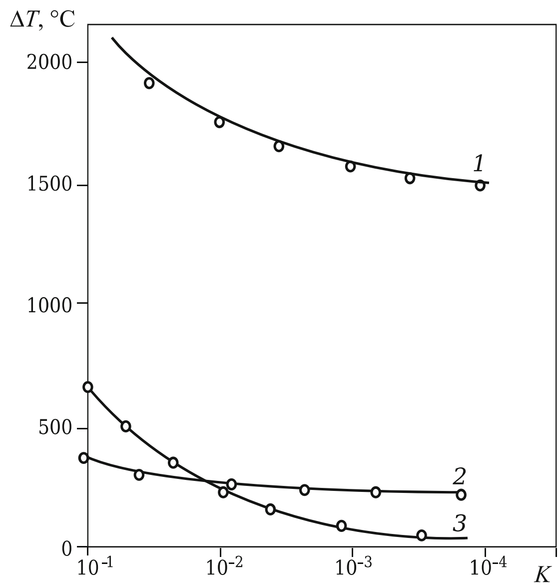

Fig. 2. Resistance of inorganic radio-transparent materials to thermal shock ΔT: *1*) quartz ceramic; *2*) Pyroceram 9606; *3*) quartz based on Al_2O_3; $K = ad/2$, where d is the thickness of the wall of the product; *a*) heat-transfer coefficient.

perature gradient through the thickness of the wall of the radome that the housing can withstand without failing.

Figure 2 shows how the temperature gradient ΔT depends on the quantity $K = ad/2$ for a quartz ceramic (*1*), Pyroceram 9602 (*2*), and a high-alumina ceramic (*3*). In conditional units, values of K between 10^{-1} and 10^{-4} correspond to the thermal loads encountered by spacecraft when they enter the dense layers of the atmosphere. The substantial advantage that the quartz ceramic has over the other materials with respect to this parameter is attributable mainly to its favorable combination of thermal, deformational, and strength properties [6].

Most importantly, the high thermal resistance of the quartz ceramic gives it a low coefficients of linear thermal expansion (CLTEs). The value of that coefficient for the ceramic is appreciably below the corresponding values for other ceramic materials (Fig. 3*a*).

In addition, stress relaxation takes place when quartz ceramics and products based on them are heated. As has been shown by a wide range of studies, this phenomenon is seen at temperatures above 900°C. The extent to which it is manifest can increase or diminish, depending on the nature of the raw material and the structure of the finished material [7].

Thermal conductivity is another important characteristic of radome materials. When the temperature on the outside surface is above 1000°C, the temperature of the antenna block should not be allowed to exceed 200°C.

Since the construction of a forced cooling system to cool the antenna block would complicate the structure of the product for the class of missiles being considered here, the heat problem is addressed based on the heat-protective char-

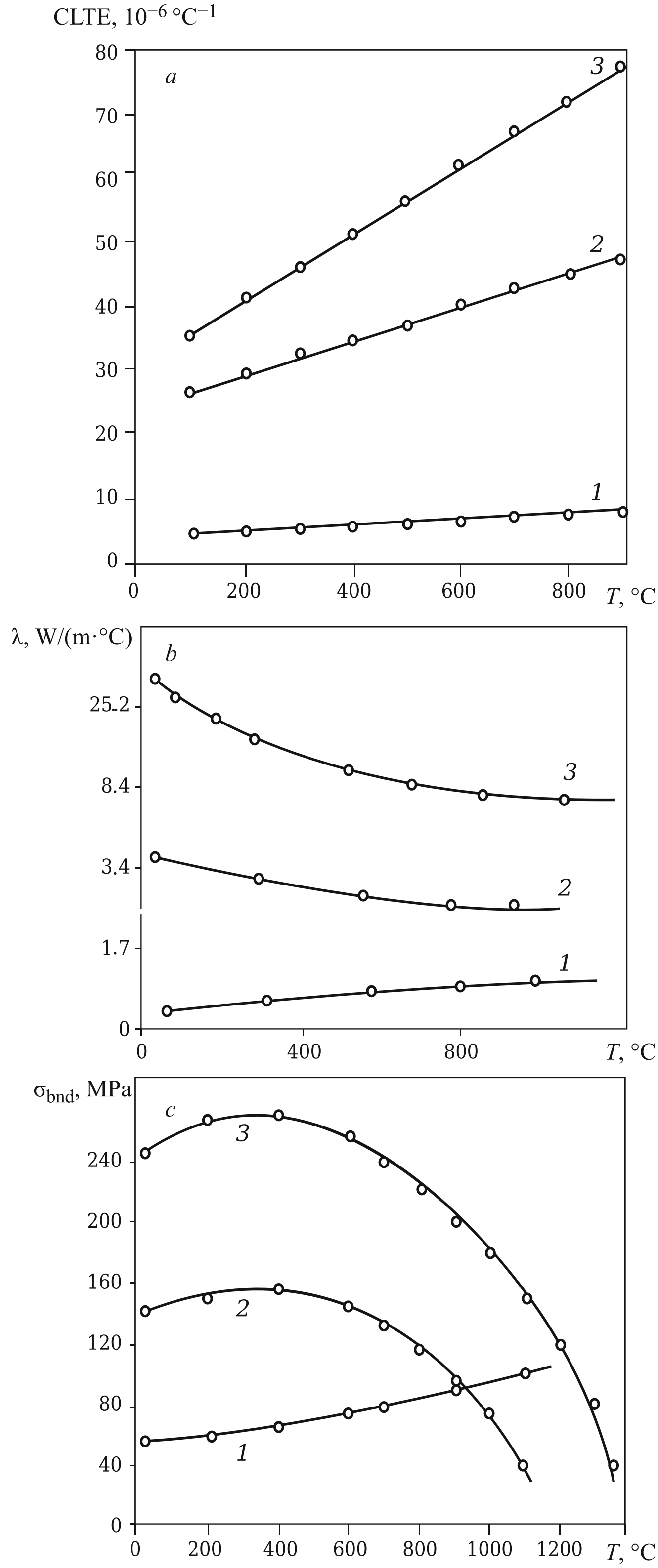

Fig. 3. Temperature dependence of the CLTE (*a*), thermal conductivity λ (*b*) and ultimate flexural strength σ_{bnd} (*c*) of inorganic materials; *1*) quartz ceramic; *2*) Pyroceram 9606; *3*) ceramic based on Al_2O_3.

acteristics of the radome material and the design parameters of the radome itself. Preference is given to materials with a low thermal conductivity. Materials based on amorphous silicon dioxide have the lowest thermal conductivity among the existing inorganic dielectrics. Figure 3b shows the temperature dependence of thermal conductivity for a quartz ceramic with a porosity of 8 – 10%, Pyroceram 9606, and a nonporous high-alumina ceramic. Thermal calculations performed as part of the design of half-wave radomes for ground-to-air missiles operating at speeds of 6 – 12 M show that only a shell made of a quartz ceramic provides adequate protection against heat [8 – 10].

Quartz ceramics have the lowest elastic and strength properties among the materials being examined here. However, these properties become closer to one another as heating occurs (Fig. 3*c*). The increase seen in the strength of quartz ceramics with an increase in temperature can also be attributed to stress relaxation that takes place with the occurrence of plastic deformation [11]. When a porous quartz ceramic is subjected to high temperatures over a long period of time (tens of hours), it begins to undergo additional sintering at 1100°C and undergoes further crystallization at temperatures above 1200°C.

However, when a product made of the material is subjected to one-sided heating, the material increases in strength and its service-temperature range is elevated to 1700 – 2000°C.

Numerous studies in Russia and abroad have shown that the high thermal resistance and low thermal conductivity of products made of quartz ceramics keeps them from losing any of their original load-carrying capacity even when part of the thickness of the shell has been lost due to the material's melting and sublimation [12 – 15]. *The deciding factor in choosing a material for a radome is the stability of its permittivity at relatively low values of the loss tangent* tgδ (Fig. 4) [6].

For quartz ceramics, the sitall Pyroceram 9606, and high-alumina ceramics, permittivity changes by 1.0, 2.7, and 4.8% respectively in the temperature range 25 – 500°C and by 3.0, 6.2, and 18.0% respectively in the range 25 – 1000°C (see Fig. 4).

The change in the value of ε of quartz ceramics is no greater than 4% up to 1200°C, and this parameter does not increase above 4.1 even when the quartz glass melts ($T = 1800 – 2000$°C) [16]. The low thermal conductivity of quartz ceramics under conditions whereby the product is briefly subjected to unilateral heating prevents the shell from being heated to appreciable depths and keeps high temperatures localized in a surface layer with a thickness of up to 0.5 mm. Such an outcome does not seriously interfere with the performance of the radome in terms of its electronic characteristics.

The absolute value of permittivity is also very important from the standpoint of ensuring that the radar characteristics of a radome are satisfactory. This value is lowest for quartz ceramics (Fig. 4*a*), which not only alleviates distortion of the antenna's directivity diagram and reduces its SHF losses

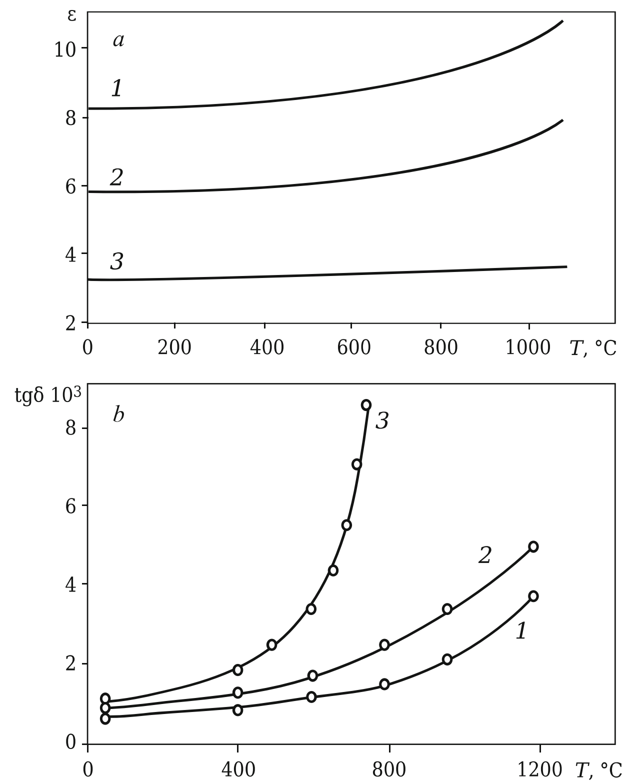

Fig. 4. Temperature dependence of the permittivity ε (*a*) and tgδ (*b*) of inorganic radio-transparent materials: *1*) quartz ceramic based on Al_2O_3; *2*) Pyroceram 9606; *3*) quartz ceramic.

but also simplifies the machining of the shell. Machining is made easier in this case because the requirements on the wall-thickness tolerance are less demanding for quartz ceramics than for other materials [1]. Whereas the tolerance is 0.1 mm for radomes made of a quartz ceramic with $\varepsilon = 3.3 – 3.5$, it is 0.01 and 0.001 mm respectively for radomes made of sitalls with $\varepsilon = 6 – 8$ and radomes made of alumina ceramics with $\varepsilon = 9 – 10$.

According to the data in [17 – 21], the permittivity of the radome material should not vary more than 10% within the working temperature range and the value of tgδ should be no higher than 0.01. However, these requirements might be tightened for actual service conditions.

One large advantage that quartz ceramics have is that they are well-suited for industrial processing. The manufacture of products made of quartz ceramics does not require expensive equipment and the raw materials can be quartz-bearing materials commonly found on the Earth's surface - vein quartz, quartz concentrates, and glass sands. Various types of wastes generated in the production of quart glass can also be used. Let us compare the manufacture of products made of high-alumina ceramics, sitalls, and quartz ceramics. In the first case. the products are formed by hot slip casting with the addition of more than 10% organic binder. The binder is subsequently burned out of the product, a process which forms hazardous substances. In the second case, products are

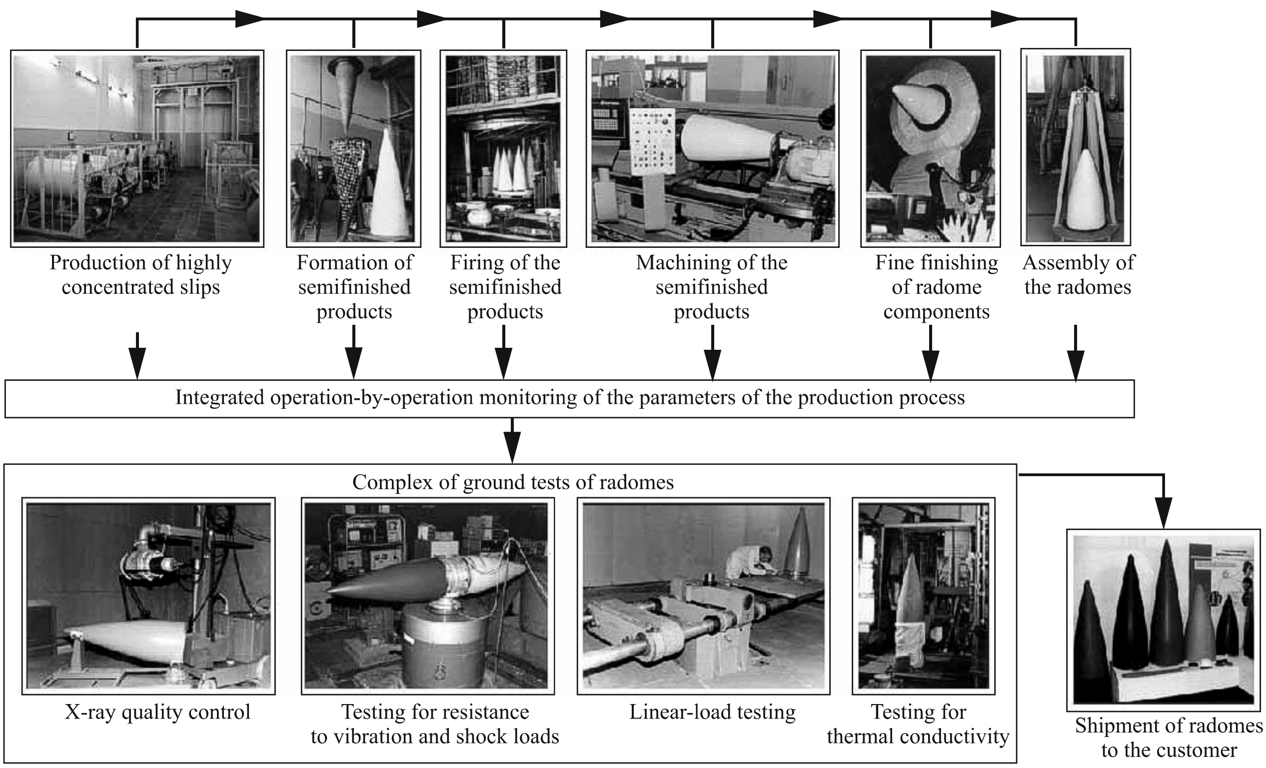

Fig. 5. Flow diagram for the production of radomes made of quartz ceramics.

formed from a glass melt at high temperatures. Products made of quartz ceramics are easily made by aqueous slip casting in standard gypsum molds. Products made of quartz ceramics are fired at 1240 – 1270°C in easy-to-operate electric furnaces (instead of the high-temperature gas-fired furnaces used to fire products of Al_2O_3 at 1650°C). The low hardness of products composed of quartz ceramics makes them relatively easy to machine. Here, it must be taken into account that the conditions for the production of quartz-ceramic products with small machining tolerances are created as a result of the small amount of linear shrinkage which occurs during firing (up to 1.5% of a quartz ceramic, versus 10% for a high-alumina ceramic) and the fact that slip casting is more convenient than (for example) the centrifugal forming of sitall products. Thus, the overall production process is simplified appreciably and fewer raw materials and auxiliary materials are consumed during the course of it. The development by specialists at ONPP "Tekhnologia" of a new technology for obtaining highly concentrated slips and dense, strong castings [7, 8] has made it possible to successfully introduce the production of large (up to 1.5 m) products. This is an advance that to this point has not been realized for other materials (Fig. 5).

TABLE 3. **Generalized Comparative Characteristics of Inorganic Radio-Transparent High-Heat-Resistance Materials**

Material	Main advantages	Disadvantages
Quartz ceramics	Highly heat-resistant material and thermal-shock-resistant radome; stability of the dielectric characteristics within broad ranges of temperature and frequency; good heat-protection characteristics; suitability for the industrial manufacturing of products of complex shape	Low mechanical strength; need for protection against moisture and hermetization; low resistance to erosion by dust and rain
Glassy-crystalline materials (sitall, Pyroceram)	Absence of porosity; high resistance to climatic effects and seawater	Inadequate heat resistance and inadequate thermal stability of the dielectric properties
High-alumina ceramics	High strength of the material and the shell; good resistance to rain-induced erosion and the effects of aggressive media	Low resistance to thermal shock; high sintering temperature

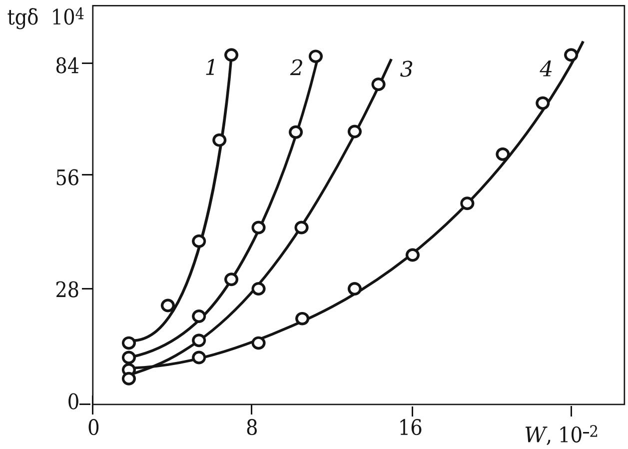

Fig. 6. Dependence of tgδ for a quartz ceramic on moisture absorption W and porosity, %: *1*) 6.8; *2*) 11.5; *3*) 16.3; *4*) 18.7.

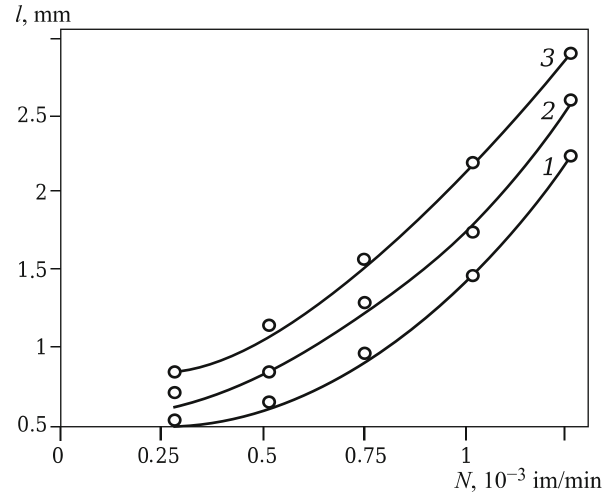

Fig. 7. Dependence of the depth of the damage l to a quartz ceramic with a porosity of 8.5% on the intensity of the drop load N for different impact velocities, m/sec; *1*) 120; *2*) 150; *3*) 180.

An analysis of the level of the physico-technical properties and technological potential of these materials (Table 3) shows that in world metallurgy no one has yet succeeded in finding a single material or composite that can satisfy all of the existing requirements for radomes. This situation is forcing scientists and engineers to restrict the areas of application of materials based on the conditions encountered in making radomes for specific systems.

For example, a quartz ceramic with a porosity of 8 – 10% is widely used in the different models of radomes used in S-300 missile systems (in Russia), Patriot missiles (in the U. S.), and other systems that employ protective mobile launch containers. At the same time, the use of quartz ceramics for the radomes of airfield- and ship-based missile systems is problematic [22, 23] due to these materials' relatively low mechanical strength, the possibility of their absorbing moisture from the environment (Fig. 6), and their low resistance to erosion initiated by dust and rain (Fig. 7).

Sitalls and alumina ceramics are widely used in the U. S. for the types of missiles just mentioned. Most airfield- and ship-based missiles in Russia are equipped with sitall radomes because this class of materials is easier to work with under factory conditions compared to alumosilicate ceramics, in addition to having clear advantages in terms of many of their physico-technical characteristics.

In light of the valuable properties of quartz ceramics and sitalls, repeated attempts have been made to combine them into a single complex and create a material that simultaneously has high thermal resistance, high values for permittivity and strength, low porosity, and stable dielectric and strength characteristics within a broad range of temperatures.

However, an analysis of the results obtained in studies of the modification of quartz ceramics with oxides and other compounds in order to obtain new properties shows that although these attempts have only solved certain problems encountered locally, their results are important and are needed by industry (Fig. 8). No comprehensive solution has yet been found. On the one hand, the crystallization of quartz glass has prevented this material from being sintered to zero porosity by the introduction of a large number of modifying additions. On the other hand, the nonporous quartz ceramics that have been produced cannot take the place of sitall radomes due to their relatively low strength and permittivity. This makes it necessary to increase the thickness of the wall of the radome [20] and its weight. Moreover, industry is oriented toward the production of control devices based on the properties of sitalls. As a result, a simple substitution of one material by another would make it necessary to redesign missiles and restructure the entire process of making their control systems — a very difficult, lengthy, and costly proposition. Table 4 shows the main properties of amorphous-silica-based materials with a porosity from zero to 85%.

Similar to the efforts that have been made to standardize the properties of quartz ceramics, researchers have been conducting studies to improve the properties of existing sitalls used in electronic applications. The main emphasis of these studies is on improving their thermal resistance and mechanical strength and stabilizing their dielectric characteristics.

A thorough analysis was made of the factors that prevent realization of sitalls' complex of valuable properties, specifically: the presence of bubbles, cavities, internal and surface defects, structure, phase composition, and production conditions [24 – 33]. The analysis made it possible to devise means of improving the mechanical strength and thermal resistance of sitalls and stabilizing their dielectric characteristics.

It was shown in [34, 35] that the use of certain measures in the production of sitalls (correction of the chemical composition of the original glass, increasing the length of time the material is held at the crystallization temperature by a

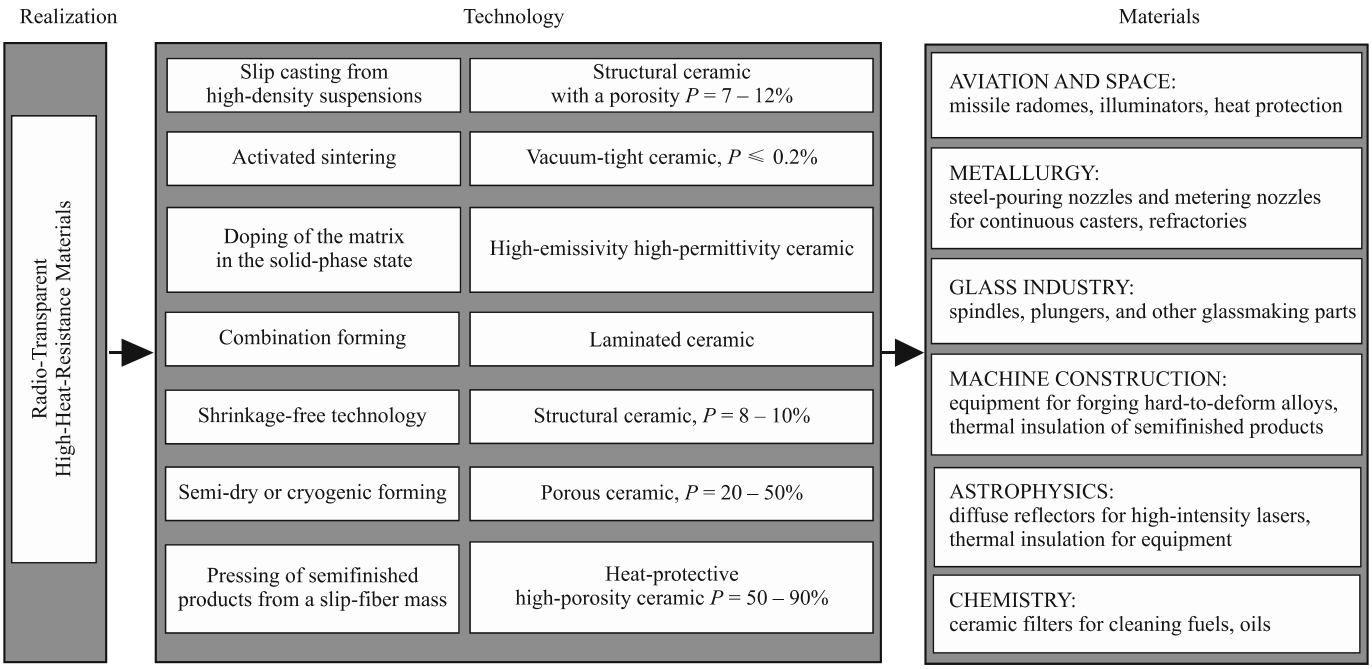

Fig. 8. Areas of application of ceramics based on amorphous silicon dioxide.

factor of up to 10) makes it possible to stabilize the dielectric characteristics of sitalls at temperatures up to 600 – 700°C.

The studies referred to above and many other investigations show that a wide-ranging search is under way to find methods and equipment for improving the properties of radar-grade sitalls. The available equipment is inadequate to this task, which is in part due to the sitall manufacturing process. The nature of that process makes it extremely difficult and sometimes impossible to significantly alter the chemical composition of the original glasses.

First of all, the need to ensure that the composition of a sitall is such as to allow its vitrification and ensure that the melt has the required properties makes it impossible to obtain sitalls based mainly on crystalline phases. Thus, in addition to oxides that correspond to the composition of the prescribed crystalline phase, a large group of other additional components needs to be added to the melt. The addition of those components can prevent the formation of the desired phase or sharply reduce its concentration.

Secondly, the existence of an upper limit on the founding temperature (~1600°C) makes it impossible to create sitalls based on high-melting phases. The existence of this limit therefore also makes it impossible to obtain heat-resistant materials.

Sitalls became the main material used in the former USSR and abroad to make radomes for airfield-based and ship-based missiles despite all of the apparent shortcomings of the classic (glass-based) technology for manufacturing them. Among the shortcomings is the need to prepare a charge of a prescribed chemical composition, found the glass, form products by centrifugal casting, pressing, or roll-

TABLE 4. **Main Properties of Radio-Transparent Ceramic Materials Based on Amorphous Silicon Dioxide***

Indices	Grade of material						
	TSM-109	TSM-107	Niasit	OTM-920	OTM-921	OTM-607	OTM-605
Density, g/cm^3	2.10 – 2.15	2.15 – 2.18	1.94 – 2.05	1.70 – 1.75	1.26 – 1.33	0.5 – 0.6	0.3 – 0.4
Porosity, %	5 – 10	<0.5	8 – 10	21 – 25	40 – 43	70 – 80	82 – 86
Ultimate flexural strength, MPa	65	55	45	28	20	9	3
Thermal conductivity, W/(m·°C)	1.8	1.5	0.7	0.6	0.4	0.1	0.07
CLTE, 10^{-7} deg^{-1}	≤9.5	≤7.5	≤7.5	≤7.5	≤7.5	≤7.5	≤7.5
Permittivity, f = 1010 Hz, 20°C	5.5	3.7	3.5	2.9	2.5	1.5	1.3

* Increase in the range 20 – 1200°C ε < 3%; tgδ < 0.005.

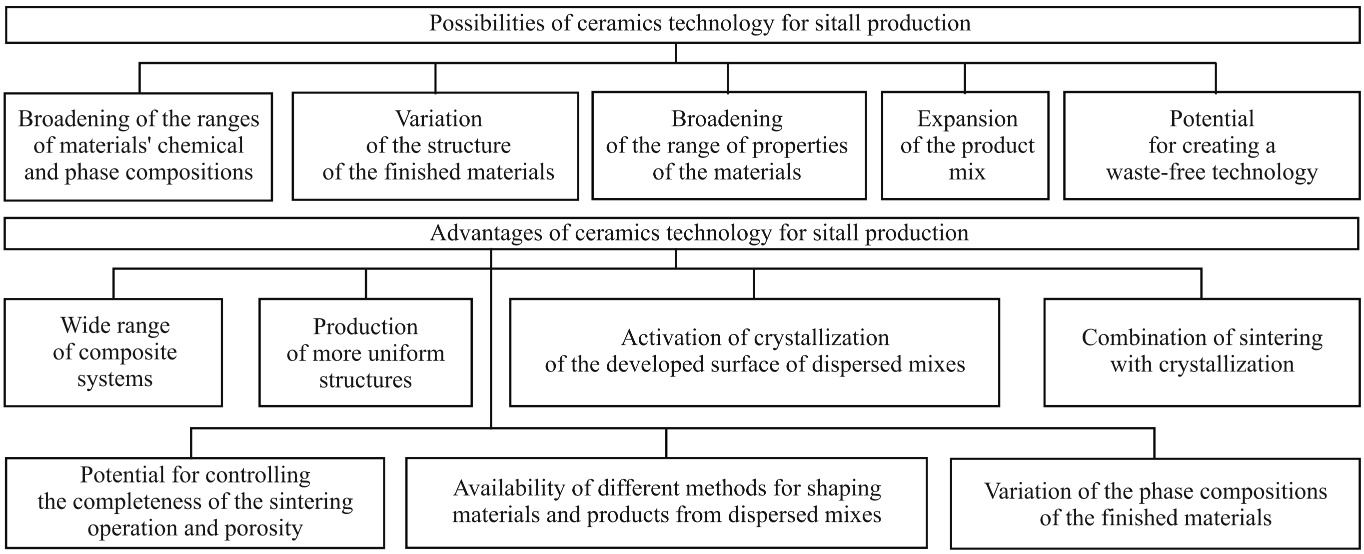

Fig. 9. Possibilities and Advantages of Ceramics Technology for Obtaining Sitalls in Comparison to the Traditional Technology.

ing and then fire them, and have the products undergo crystallization and machining.

Hundreds of compositions of sitalls have now been synthesized, but industry has mastered the production of only a small percentage of them, and just a few are used to make radomes. The sitalls that are the most promising for radome production are the sitalls in the system SiO_2–Al_2O_3–MgO (Pyroceram 9606 (U. S.), AS-370 and AS-023 (Ukraine)) and in the system SiO_2–Al_2O_3–Li_2O (Pyroceram 9608 (U. S.) and AS-418 (Ukraine)). The sitalls of the first system do not contain ions of alkali metals, which gives them small dielectric losses. However, their thermal resistance is low due to their high CLTE. The sitalls of the second group have worse values for the loss tangent but are more heat-resistant due to their low CLTE. The main crystalline phases in the sitalls of the first group: cordierite $2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$, rutile TiO_2 a β-quartz solid solution. The main crystalline phases of the sitalls in the second group: a solid solution of β-spodumene $Li_2O \cdot Al_2O_3 \cdot 4SiO_2$, rutile TiO_2, and a solid solution of β-eucryptite $Li_2 \cdot Al_2O_3 \cdot 2SiO_2$. Table 5 shows the main physico-technical properties of these sitalls according to data from Russian and foreign sources.

The values of the indices for the properties of materials belonging to a given system are similar, which indicates that the possibilities of the system have been exhausted. As a result, researchers have recently been paying more attention to ceramics technology for synthesizing glassy-crystalline materials. The essence of this area of technology is the granulation of a glassy melt by a jet of water, comminution of the granules to obtain a powder, use of the powders to form semifinished products by semi-dry pressing or thermoplastic die casting with the use of binders (a paraffin plasticizer,

TABLE 5. **Main Properties of Glassy-Crystalline Materials Used to Make Radomes**

Indices	Value of the indices for different materials			
	Pyroceram 9606 (U. S.)	AS-370 (Ukraine)	Pyroceram 9608 (U. S.)	AS-418 (Ukraine)
Density, g/cm^3	2.60	2.6 – 2.7	2.5	2.5 – 2.6
Water absorption, %	0	≤0.02	0	≤0.02
Ultimate flexural strength (20°C), MPa	120 – 260	170 – 210	110 – 130	100 – 145
Elastic modulus, MPa	12.3	13.2	8.8	9.0
CLTE (20 – 600°C), 10^{-7} deg^{-1}	15 – 57	20 – 40	4 – 20	5 – 22
Thermal conductivity (20 – 600°C), kJ/(kg·deg)	3.0 – 2.2	3.1 – 2.1	1.8 – 2.0	1.8 – 2.0
Specific heat capacity (20 – 600°C), kJ/(kg·deg)	0.8 – 1.3	0.9 – 1.3	1.75 – 1.2	0.5 – 1.1
Permittivity ($f = 10^{10}$ Hz, 20°C)	5.7	6.7	6.9	7.5
Loss tangent ($f = 10^{10}$ Hz, 20°C)	0.0002	0.0012	—	0.015
Thermal resistance ΔT, °C	350	400	550	600

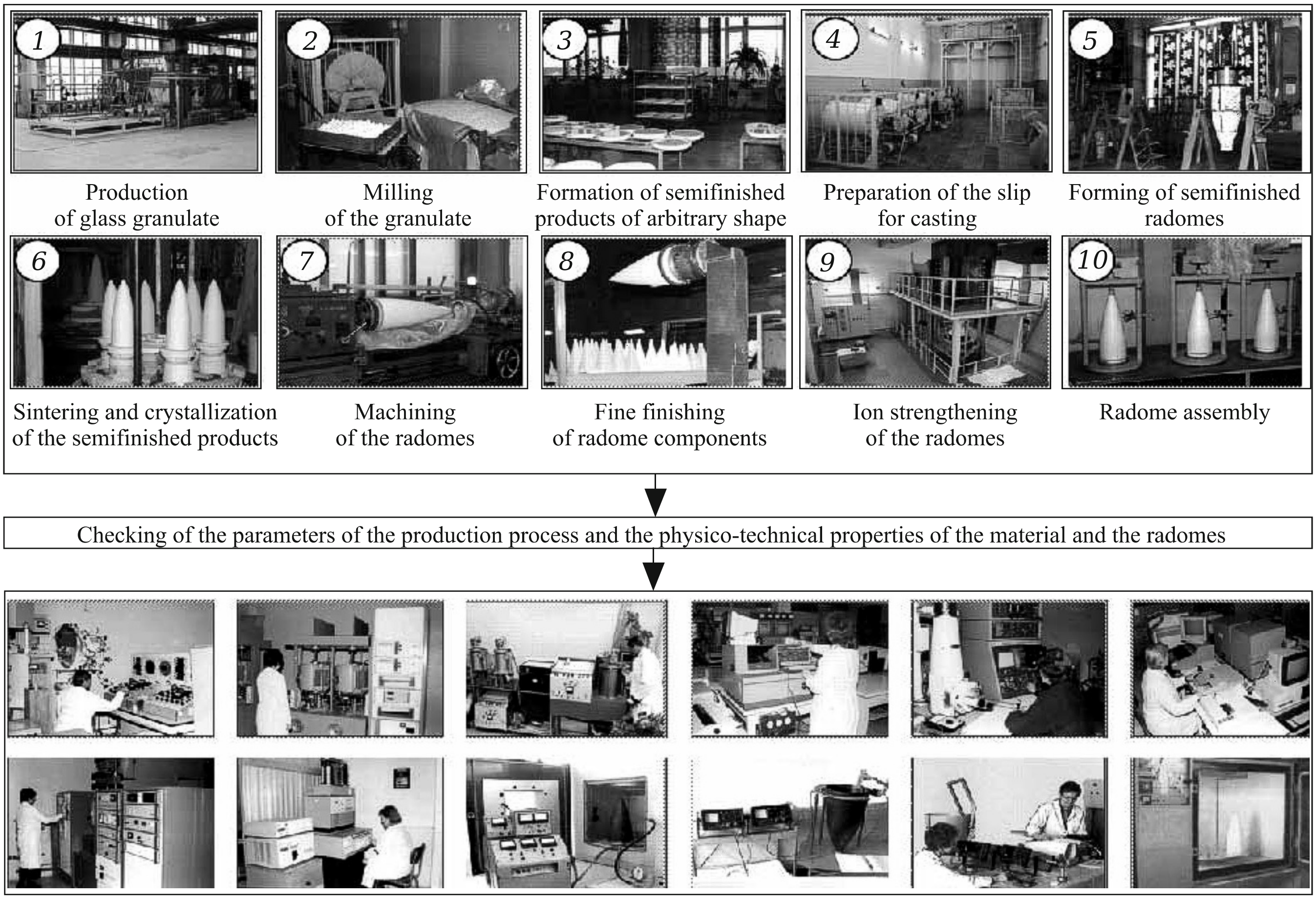

Fig. 10. Flow chart of the production of radomes from glassy-ceramic materials.

polyvinyl alcohol, or organosilicon binders), and sintering and crystallization of the material [33 – 46].

Figure 9 shows generalized data on the possibilities and advantages of the use of ceramics technology to produce sitalls instead of the traditional (glass-based) technology.

The ceramics technology has an advantage over the conventional technology because it yields semifinished products with minimal variations in thickness. Also, there is little or no regulation of the configuration or shape that can be imparted to the product. Another important feature of sitall production by ceramics technology is that the heat treatment is significantly shorter and simpler because the developed surface of fine glass powders can act as a catalyst [36, 39]. The possibility of producing medium- and high-porosity sitalls is yet another advantage of the ceramics technology. It was shown in [38, 41] that it is possible to obtain β-spodumene ceramics by thermoplastic casting and subsequent sintering at 1000 – 1250°C. The semifinished products have a porosity ranging from 1 to 40% and an ultimate flexural strength of up to 90 MPa.

The use of ceramics technology for making glassy-crystalline materials makes it possible to combine the process of sintering the material with crystallization of the glass; it allows the use of different methods of forming products from dispersed mixes, including the aqueous slip casting of semifinished products [46]; it provides an opportunity for the utilization of industrial wastes, is indispensable for low-volume production, and is well-suited for use in applications in which changes to the product mix occur frequently or must be executed quickly.

Wide-ranging prospects for creating glassy-crystalline materials with a qualitatively new level of property indices are created by using the latest advances in modern technology: matrix reinforcement, sol-gel processes, reaction phase-forming, and other methods.

On the whole, the results obtained from an analysis of the current state of R&D work on the synthesis of glassy-crystalline materials show that new methods are quickly being developed and new directions are being pursued in the technology of sitalls.

The ONPP "Tekhnologiya" believes that the ceramics-based approach to synthesizing materials and developing new technologies for making sitall radomes is the proper approach to take, since the company has more than 30 years of experience in making radomes from ceramics based on SiO_2 and Al_2O_3. It is organizing its efforts to make new radomes as part of a program that considers all aspects of this undertaking — from creating the specifications for the radome to its manufacture. Thus, the manufacturing process as a whole includes performing electrodynamic and heat-resistance computations at the design stage, inventing the technologies and materials that are needed, preparing and ground-testing

TABLE 6. **Properties of Glassy-Ceramic Materials Obtained by the New Technology**

Indices	Material						
	OTM 357	OTM 357-5	OTM 357-10	OTM 357-15	OTM 357-20	OTM 357-U	OTM 357-O
Density, g/cm^3	2.5	2.56	2.61	2.67	2.71	2.5	2.5
Porosity, %	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1
Ultimate strength MPa:							
in bending (20 – 1150°C)	100 ± 10	100 ± 10	100 ± 10	100 ± 10	100 ± 10	137	120 ± 10
in compression	300 ± 30	300 ± 30	300 ± 30	300 ± 30	300 ± 30	—	—
Elastic modulus, 10^{-4} MPa	5.4	5.5	5.7	5.7	5.6	6.9	7.3
CLTE (20 – 900°C), 10^{-7} deg^{-1}	5 – 13	7 – 15	8 – 16	11 – 21	13 – 23	6 – 17	8 – 17
Thermal conductivity (20 – 700°C), W/(m·°C)	1.6 – 1.9	1.7 – 1.9	1.8 – 2.0	2.1 – 2.4	2.2 – 2.5	1.6 – 2.3	1.8 – 2.2
Specific heat capacity (20 – 700°C), kJ/(kg·°C)	0.9 – 1.2	0.9 – 1.2	0.9 – 1.2	0.9 – 1.2	0.9 – 1.2	0.8 – 1.3	3.80 – 1.27
Impact toughness, kJ/m^2	2.2 – 2.5	2.1 – 3.1	2.0 – 2.5	2.0 – 2.4	1.9 – 2.3	≥2.5	2.2 – 2.3
Permittivity (f = 10^{10} Hz, 20°C)	6.9 – 7.3	7.8 – 8.1	8.8 – 9.5	10.2 – 10.5	11.5 – 12.5	6.5 – 7.5	6.5 – 7.5
Increase in permittivity (f = 10^{10} Hz, 20 – 700°C), %	≤4.5	≤4.5	≤4.0	≤4.0	≤3.0	≤6.0	≤3.0
Loss tangent (f = 10^{10} Hz, 20 – 700°C)	0.01 – 0.06	0.013 – 0.07	0.012 – 0.075	0.013 – 0.07	0.013 – 0.07	0.01 – 0.06	0.01 – 0.05
Thermal resistance ΔT, °C	1200	1150	1150	1100	1000	—	—
Friction resistance, point rating	1	1	—	—	—	—	—

TABLE 7. **Methods Used to Expose Test Specimens of a β-Spudomene Glass-Ceramic to the Factors that Products Made of It Will Encounter in Service**

Parameters and sequence of exposure to different factors				
1	2	3	4	5
Simulation of exposure to dust during 50 takeoffs and landings of the carrier: – diameter of the particles of quartz sand ≤0.3 mm; – angle of impact 15°; – dust content of the air 10 g/m^3 – working distance in one cycle 500 m (σ_{bnd} = 112 MPa, W ≤ 0.1%)	Simulation of the effects of rain during 50 joint takeoffs and landings: – diameter of the water drops 2 mm; – impact angle 15°; – water content of the rain cloud 1 g/m^3; – time of flight through rain cloud in 1 cycle 30 min (σ_{bnd} = 105 MPa, W ≤ 0.1%)	Simulation of the effect of variable temperatures over 50 takeoffs and landings of the plane with the carrier: – (−60 + 150)°C (σ_{bnd} = 110 MPa, W ≤ 0.1%)	Simulation of the effects of rain during independent flight of the missile: – diameter of water drop 2 mm; – speed of impact 1280 m/sec; – angle of impact 15°; – water content of rain cloud 1 g/m^3 (σ_{bnd} = 112 MPa, W ≤ 0.1%)	Simulation of temperature factors during independent flight of the missile: – heating rate 200°C/sec; – t_{max} = 1200°C; – holding time 33 sec; – cooling rate 100°C/sec (σ_{bnd} = 112 MPa, W ≤ 0.1%)

Properties of the specimens: dimensions 7 x 7 x 45 mm, σ_{bnd} = 104 MPa, W ≤ 0.1%
Influential factors and their sequence

1 + 2	1 + 2 + 3	1 + 2 + 3 + 4	1 + 2 + 3 + 4 + 5
(σ_{bnd} = 115 MPa, W ≤ 0.1%)	(σ_{bnd} = 110 MPa, W = 0.1%)	(σ_{bnd} = 105 MPa, W ≤ 0.1%)	(σ_{bnd} = 109 MPa, W ≤ 0.1%)

TABLE 8. **Effect of Chemical Treatment on the Dielectric and Strength Properties of the Glass-Ceramic***

Reagent	Concentration, %	Ultimate flexural strength***, MPa	Permittivity*** at $f = 10^{10}$ Hz	tgδ*** at $f = 10^{10}$ Hz, 10^4
HCl	18.5	115 / 120	6.95 / 6.94	105 / 110
H_2SO_4	24.9	115/115	6.85 / 6.85	105 / 109
HNO_3	32.0	115 / 108	6.95 / 6.94	105 / 110
H_3PO_4	16.5	115/116	6.90 / 6.89	105 / 110
$NaOH + Na_2CO_3$**	4.0 5.3	115 / 109	7.07 / 7.07	110 / 114
$KOH + Na_2CO_3$**	5.6 5.3	115/115	6.93 / 6.92	106 / 105

* Boiling time 3 h.
** Mixture of different volumes.
*** Numerator – initial value; denominator — final value.

TABLE 9. **Chemical Stability of the Glass-Ceramic in Sulfuric Acid and Sodium Hydroxide in Accordance with GOST 473.1 and GOST 473.2***

Reagent	Concentration, %%	Chemical stability, %	
		acid resistance	alkali resistance
Powder of the original glass granulate			
H_2SO_4	98	94.23	—
NaOH	35	—	22.41
Powder of the glass-ceramic			
H_2SO_4	98	94.87	—
NaOH	35	—	52.36
Glass-ceramic in the form of disks			
H_2SO_4	98	99.73	—
NaOH	35	—	90.43

* Boiling time 1 h.

specimens, beginning serial production, and delivering the product to customers.

As the main variant for research on this endeavor, we chose to use a lithium-alumosilicate glass because of the satisfactory technical characteristics of sitalls based on this material and the fact that they are already being used to make radomes for the Russian military. The base technology that was chosen is aqueous slip casting, which allows the production of a new class of glassy-crystalline materials and the fabrication of large high-density semifinished products of complex shapes. Those possibilities in turn make it possible to produce nonporous radomes at minimal cost [47 – 54]. The given technology combines elements of ceramics- and glass-based technologies for producing glassy-crystalline materials and products and makes maximum use of the equipment already employed in the fabrication of glassy-crystalline and quartz radomes. Thus, existing production facilities can continue to be used as the product mix

TABLE 10. **Chemical Stability of the Glass-Ceramic during Long Exposure to Aggressive Media**

Aggressive medium	Concentration, %	Time of exposure, %	Loss of mass, %	Chemical stability, %
HI	18.5	2650	0.03	99.97
H_2SO_4	24.9	2650	0.02	99.98
H_3PO_4	16.5	2650	0.02	99.98
Kerosene	—	2650	0.01	99.99
Seawater	—	5800	0.0	100

TABLE 11. **Properties of the Glass-Ceramic at the "Curing" Temperature over 360 sec while It is Unilaterally Heated at a rate of 100°C/sec (inertial cooling)**

Indices	Initial value	Property indices at the "curing" temperature, °C						
		450	650	850	1000	1050	1100	1200
Density, g/cm^3	2.49	2.50	2.49	2.49	2.50	2.48	2.49	2.50
Water absorption, %	0.04	0.05	0.03	0.04	0.02	0.01	0.02	0.03
Ultimate flexural strength, MPa	117	118	122	124	120	121	119	123
Permittivity	7.24	7.27	7.27	7.25	7.21	7.24	7.23	7.22

is altered (Fig. 10). The main properties of the materials that are obtained by the ceramics-based technology are shown in Table 6. Table 7 shows the materials' resistance to the adverse factors encountered during the operation of air-to-air and air-to-surface missiles, Tables 8 – 10 show their resistance to the effects of aggressive media, and Tables 11 and 12 show the results of high-temperature tests.

We will not use this article to explore the feasibility of employing heat-resistant radio-transparent materials based on Si_3N_4 to make radomes. However, despite the whole range of positive properties (retention of strength at high temperatures, a comparatively low permittivity, suitability for the industrial production of radomes, etc.) that will make it possible to significantly improve the TTCs of missiles, there are still at least three main problems that need to be addressed: significantly decrease thermal conductivity; ensure the attainment of vacuum-tightness; ensure the stability of the materials' radar characteristics in the working-temperature range of objects.

Proceeding on the basis of current trends in the development of aviation and missile technology for the near term, the requirements that the materials of radio-transparent radomes must meet will undoubtedly become more stringent and the materials' properties will have to attain the values shown below (within the working-temperature range):

Working-temperature range, °C	–60 + 1500
Duration of the load (in minutes) at the below working temperatures, °C:	
300	20.0
1500	5.0
Ultimate flexural strength, MPa	≥150
CLTE, 10^{-7} deg^{-1}	≤20.0
Thermal conductivity, W/(m·°C)	≤3.0
Change in ε, %	≤5.0
tgδ	≤0.01
Water absorption, %	≤0.1

Current requirements could be met by organically combining the properties of a whole range of radio-transparent materials.

Of course, it will be extremely difficult to satisfy all of the increasingly demanding requirements on the TTCs of specific missile systems just by improving the physico-technical properties of specific materials. Conforming to future standards will also be facilitated by improvements in radome design, including coordinating work on those properties with the work of the designers of missiles' control systems. Thus, future success in the solution of new and more challenging problems concerning the development of radomes depends on the close interaction of three components: the material of the radome, the design of the radome, and the technology used to make it. Each part of this triad can make its own important contribution to attainment of the ultimate goal.

Regarding the technological aspect in particular, extremely little attention has been given to the use of elements of nanotechnologies, matrix reinforcement, SHF sintering, etc.

As concerns the materials science aspect, more emphasis should be placed on the development of laminated materials and materials with heat-reflecting, vacuum-tight, erosion-resistant, and impact-proof coatings.

In addition to creating new alloys for the transitional sections as part of plan for radome design, it would be expedient to also consider using zero-CLTE composites or redesigning these sections to eliminate the effect of the airframe on the radome and provide thermal protection for the radome itself.

Further work on the elements of the above-mentioned triad can significantly improve the economic and quality indices of the quartz ceramics and glass-ceramics which are currently used for missile radomes. These elements can also help solve the numerous problems that are being encountered in attempting to use other materials for radomes.

REFERENCES

1. V. V. Pavlov, Materials for Radomes, ONTI, VIAM, Moscow (1966).
2. V. F. Bychko, "Comparative TTCs of Russian surface-to-air missile and the "Patriot" surface-to-air missile," V. F. Bychko and V. I. Nikimin, Byulleten' Inostrannoi Nauchnoi i Tekhnicheskoi Informatsii (BINTI) "Natural Sciences, Engineering," Ser. 1, No. 14 (2624), 25 (1993).
3. D. Sokolov, The Weakness of America's Air Defense [in Russian], Kommersant, No. 2, 27 – 34 (1997).
4. V. P. Morozov, V. A. Obukhovich, S. I. Sidorenko, et al., Encyclopedia of Modern Military Aviation [in Russian], Kharvei, Minsk: AST, Moscow (2001).
5. A. B. Shirokorad, Encyclopedia of Russian Missile Weaponry [in Russian], AST, Moscow; Kharvei, Minsk (2003).
6. Ya. A. Shneiderman, "New materials for the radomes of supersonic airplanes and missiles," *Zarubezhnaya Radioelektronika*, No. 2, 79 – 113 (197.
7. Yu. E. Pivinskii and A. G. Romashin, Quartz Ceramics [in Russian], Metallurgiya, Moscow (1974).
8. A. G. Romashin, E. I. Suzdal'tsev, and M. Yu. Rusin, , "Scientific and practical aspects of the manufacture of large products of complex shape made of quartz ceramics," *Novye Ogneupory*, No. 9, 34 – 40 (2004); Ibid., No. 11, 20 – 27.
9. F. Ya. Borodai, "Prospects for the development and use of ceramics based on quartz glass," *Zharoprochnye Neorganicheskie Materialy*, No. 4, 63 – 75 (1977). ONTI, NITS, Moscow.
10. E. I Suzdal'tsev, "Properties of Quartz Ceramics," *Neorganicheskie Materialy*, **20**(2), 335 (1984).
11. L. G. Podobeda, A. G. Romashin, and F. Ya. Borodai, "High-temperature radio-transparent structural ceramic," *Zharoprochnye Neorganicheskie Materialy*, No. 3, 189 – 199 (1974). ONTI, NITS, Moscow.
12. E. I. Suzdal'stev, S. M. Brekhovskiki, and V. S. Tsyganenko, "Heat-resistant materials based on quartz ceramics with good erosion resistance," *Aviats. Promst.*, No. 7, 63 – 64 (1981).
13. G. A. Frolov, A. A. Korol', V. V. Pasichyi, et al., "Characteristic temperatures of changes of state for unilaterally heated quartz ceramics," *Inzh.-Fiz. Zh.*, **51**(6), 932 – 939 (1986).
14. G. A. Frolov, V. V. Pasichnyi, E. I. Suzdal'tsev, et al, "Measurement of temperature fields in specimens of a glass-ceramic as its surface undergoes ablation," Ibid., **57**(2), 313 – 318 (1989).

15. I. I. Pen'kov, M. Yu. Rusin, and E. I. Suzdal'tsev, "Effect of receptor additives on the erosion resistance of quart ceramics," *Aviats. Promst.*, No. 7, 52 – 53 (1984).
16. E. I. Suzdal'tsev and M. Yu. Rusin, "Patterns of change in the dielectric properties of quartz ceramics," Ibid., No. 9, 54 – 56 (1984).
17. V. A. Kaplun, SHF Radomes, Sovetskoe Radio, Moscow (1974).
18. Ya. A. Shneiderman, "Materials for the radomes of supersonic airplanes and missiles," *Zarubezhnaya Radioelektronika*, No. 9, 94 – 120 (1966).
19. B. A. Prigoda and V. S. Kokun'ko, Aircraft Radomes [in Russian], Mashinostroenie, Moscow (1970).
20. L. A. Beresnevich, Production of a High-Permittivity Ceramic with a Quartz-Glass Matrix and Study of Its Properties: Engineering Sciences Candidate Dissertation, Moscow (1975).
21. V. V. Dem'yanov and E. B. Brig, "Dependence of the TTCs of radomes on the values of ε and tnη of the material of the half-wave wall," Proc. 3rd All-Union Conference on Radomes and Antenna Housings, Kharkov (1978), pp. 75 – 76.
22. E. I. Suzdal'tsev and Yu. P. Semizorov, "Effect of processing factors on the erosion resistance of quartz ceramics," *Aviats. Promst.*, No. 6, 75 – 76 (1978).
23. N. V. Solomin, F. Ya. Borodai, and N. Yu. Komissarova, "Dielectric properties of quartz ceramics," *Elektron. Tekh.*, Ser. 14, No. 3, 25 – 31 (1968).
24. Z. L. Zhur'yari, T. A. Rozhkova, V. M. Cheban, et al., "Features of the production of cordierite sitalls suitable for strengthening," *Steklo Keram.*, No. 9, 11 – 12 (1991).
25. V. N. Dubovik and O. A. Nepomnyashchii, "Defectiveness of cordierite sitalls," Catalyzed Crystallization of Glass: Symposium. MPSM SSSR, Moscow (1986), pp. 98 – 102.
26. A. M. Raikhel' and L. G. Ivchenko, Change in the surface and volume defectiveness spodumene sitalls during repeat heat treatment," Ibid., MPM SSSR, Moscow (1986), pp. 102 – 105.
27. A. M. Raikhel', V. N. Likhmenshtein, O. A. Nepomnyashchii, et al., "Effect of bubbles and cavities on the strength of sitalls," *Probl. Prochn.*, No. 2, 104 – 106 (1980).
28. V. N. Dubovik, V. N. Raikhel', V. N. Pavlova, and L. G. Ivchenko, "Study of the thermal resistance of sitalls," Ibid., No. 11, 60 – 65 (1981).
29. V. N. Dubovik, A. M. Raikhel', V. G. Shvedun, et al., "Contact strength of sitalls in impact," Ibid., No. 9, 84 – 86 (1981).
30. V. N. Dubovik and A. M. Raikhel', "Combination reinforcement of a damaged spodumene sitall," Ibid., No. 12, 67 – 70 (1988).
31. V. M. Gomon, V. N. Dubovik, A. M. Raikhel', et al., "Strengthening of sitalls" *Steklo Keram.*, No. 9, 9 – 11 (1991).
32. V. M. Gomon, V. N. Dubovik, A. M. Raikhel', et al., "Development of methods and a technology for strengthening structural-grade sitall products," Ibid., No. 9, 13 (1991).
33. V. N. Dubovik, A. M. Raikhel', O. A. Nepomnyashchii, et al., "Improving the strength and unit impact toughness of sitalls by combination strengthening," *Steklo Keram.*, No. 9 14 – 16 (1991).
34. T. V. Dubovik, "Dielectric properties of spodumene sitalls," Proc. 2nd All-Union Conf., Obninsk (1971), pp. 27 – 35.
35. V. N. Dubovik, T. V. Dubovik, and V. Ya. Sushcheva, "Dielectric properties of sitalls at SHF within the temperature range 20 – 1000°C," Catalyzed Crystallization of Glass: Symp. MPSM SSSR, Moscow (1986), pp. 75 – 79.
36. V. N. Filippovich, A. M. Kalinina, and D. D. Dmitriev, "Surface nucleation of crystals as a catalyst for the bulk crystallization of glass in the powder-based production of sitalls," Ibid., pp. 29 – 34.
37. L. K. Bondareva, N. M. Pavlushkin, G. A. Stupina, et al., "Crystallization and sintering of glass powders in the system $Li_2O–Al_2O_3–SiO_2$," *Neorg. Mater.*, **22**(9), 1487 – 1492 (1986).
38. N. M. Bobkova, S. E. Barantseva, and O. S. Zalygina, "Glass-ceramic and its properties," *Steklo Keram.*, No. 11, 16 – 18 (1995).
39. V. I. Solov'ev, "The role of crystallization catalysts in the powder production of sitalls," Catalyzed Crystallization of Glass: Symp. MPSM SSSR (1986), pp. 111 – 113.
40. V. I. Solov'ev, A. A. Leshina, I. A. Denisyuk, et al., "Dense-sintered and porous glassy-crystalline dielectrics," *Steklo Keram.*, No. 2, 16 – 18 (1992).
41. V. I. Solov'ev, E. S. Akhlestin, E. P. Sysoev, and A. A. Tryapkin, "Prospects for the development of the powder production of sitalls," Ibid., No. 3, 12 – 14 (1992).
42. Japanese Patent Application No. 56-164070, MKI C 04 B 35/16. Production of a Heat-Resistant Ceramic with Low Expansion (1981).
43. U. S. Patent No. 4194917, MKI C 04 B 35/18. Fired Ceramic Characterized by High Density and Low Thermal Expansion (1980).
44. Hungarian Patent No. 163916, MKI C 04 B 33/22. Method of Producing Heat-Resistant Ceramic Products (1975).
45. Japanese Patent Application No. 56-109870, MKI C 04 B 35/18. Sintered Material with Low Coefficient of Linear Thermal Expansion (1981).
46. German Patent No. 19622522, C 03 C 10/12. Method of Producing Shaped Products Made of a Glass-Ceramic (1998).
47. S. B. Trekhsvyatskii, V. N. Pavlov, and V. G. Strat'ev, "New glassy-crystalline material," Novye *Neorganicheskie Materialy*, No. 1, 181 – 182 (1983).
48. E. I. Suzdal'tsev, "New direction in the synthesis of glassy-crystalline radio-transparent high-heat-resistance materials," *Inzh. Fiz. Zh.*, **74**(6), 121 – 130 (2001).
49. E. I. Suzdal'tsev, "Study of the processes in the production of high-density aqueous suspensions and the formation of semifinished products made of a lithium-alumosilicate glass," *Ogneupory i Tekh. Keram.*, No. 11, 10 – 23 (2002).
50. E. I. Suzdal'tsev, "Effect of the heat-treatment conditions on the formation of the structure and properties of a lithium-alumosilicate glass and glass-ceramic," Ibid., No. 4, 16 – 25 (2002).
51. E. I. Suzdal'tsev, "Study of the production of a β-spodumene glass-ceramic with controllable permittivity," Ibid., No. 5, 15 – 18 (2002).
52. E. I. Suzdal'tsev, Synthesis of Radio-Transparent Glassy-Crystalline High-Heat-Resistance Materials and Development of a Technology for Using Them to Make Aircraft Radomes: Engineering Sciences Doctoral Dissertation, Moscow (2002).
53. E. I. Suzdal'tsev, "Statistical analysis of the process of making products composed of a lithium-alumosilicate glass-ceramic," *Ogneupory i Tekh. Keram.*, No. 3, 12 – 18 (2004).
54. E. I. Suzdal'tsev and A. S. Khamitsaev, "Resistance of a lithium-alumosilicate glass-ceramic to the factors that adversely affect aircraft in service," Ibid., No. 10, 16 – 23 (2005).