



## SYNTHESIS OF A FROST-RESISTANT SILOXANE RUBBER AND AN ELASTOMER ON ITS BASIS

Cite this: *INEOS OPEN*,  
2022, 5 (3), 74–78  
DOI: 10.32931/io2211a

Received 8 November 2022,  
Accepted 3 February 2023

<http://ineosopen.org>

M. A. Obrezkova,\*<sup>a</sup> V. V. Gorodov,<sup>a</sup> D. A. Khanin,<sup>b</sup> M. I. Buzin,<sup>b</sup>  
O. V. Bobrova,<sup>c</sup> A. V. Gorshkov,<sup>c</sup> and A. M. Muzafarov<sup>a,b</sup>

<sup>a</sup> Enikolopov Institute of Synthetic Polymeric Materials, Russian Academy of Sciences,  
Profsoyuznaya ul. 70, Moscow, 117393 Russia

<sup>b</sup> Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences,  
ul. Vavilova 28, str. 1, Moscow, 119334 Russia

<sup>c</sup> AO "MedSil", Novomytichshinskiy pr. 41A, Mytishchi,  
Moscow Oblast, 141018 Russia

### Abstract

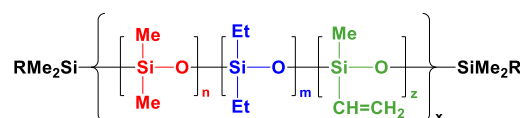
A synthetic route to frost-resistant siloxane rubbers is developed on the basis of the anionic block copolymerization of a mixture of cyclooctamethyltetrasiloxane, hexaethylcyclotrisiloxane, and 1,3,5,7-tetravinyl-1,3,5,7-tetramethylcyclotetrasiloxane in the presence of KOH. The resulting rubbers were used to produce frost-resistant elastomers. According to the results of DSC studies, the glass-transition temperature of the frost-resistant rubber is  $-129\text{ }^{\circ}\text{C}$ ; no crystallization or melting processes of the samples are detected on the thermograms. The elastomer obtained based on the siloxane rubber retains its operational characteristics even at the temperature as low as  $-123\text{ }^{\circ}\text{C}$ .

**Key words:** siloxane rubbers, anionic polymerization, frost-resistant elastomers, glass-transition temperature.

### Introduction

Elastomers based on siloxane rubbers find extensive use in different practical fields, including astronautical, aeronautical and transport engineering, building industry, agriculture, and medicine. They are in demand where the materials with a wide operating temperature range from  $-100$  to  $300\text{ }^{\circ}\text{C}$  are required. A basic and versatile material for these applications is polydimethylsiloxane (PDMS). However, despite the fact that the glass-transition temperature ( $T_g$ ) of PDMS is  $-123\text{ }^{\circ}\text{C}$ , its lower operating temperature limit is determined by the crystallization temperature of  $-40\text{ }^{\circ}\text{C}$ . To improve the thermal stability, methylphenyl- or diphenylsiloxane units, various carborane-like heterostructures [1], and other aromatic systems are introduced into the composition of PDMS. To expand the low-temperature operating range of PDMS, it is necessary to suppress the crystallization processes, which, in fact, limit its low-temperature operating range. The introduction of modifying units is also effective in this case. Indeed, the low-temperature characteristics of a silicone rubber significantly depend on its chemical composition, namely, the nature of substituents at the silicon atom [2–8].

It should be noted that there are other approaches to solving the problem of suppressing crystallization in PDMS. For example, this process is effectively suppressed by a special macromolecule organization: multiarm star-shaped polydimethylsiloxanes of various structures do not crystallize [9, 10]. In particular, the crystallization is effectively suppressed in star polymers featuring a cyclosiloxane core [11, 12]. However, these structures may have only limited application as the



modifying agents.

In industry, a solution to expanding the operating temperature range of polydimethylsiloxane rubbers is based on the introduction of methylphenyl units at the concentration of 8–10 mol % [13]. As already noted, this improves the thermal stability of the polymers and, at the same time, suppresses crystallization so that the operating temperature range of the resulting rubbers varies from  $-90$  to  $300\text{ }^{\circ}\text{C}$ . For the controlled vulcanization of rubbers [14], methylvinylsiloxane units are also introduced into their compositions in small amounts (0.1–0.001%) but their effect on the glass-transition temperature of a rubber can be neglected. Hence, the introduction of the modifying units bearing phenyl substituents at the silicon atom is a good tool for expanding the operating temperature range of silicone rubbers.

Nevertheless, this approach does not allow for realizing the huge potential of PDMS which  $T_g$  is known to exist in the low temperature range ( $-123\text{ }^{\circ}\text{C}$ ). Taking into account that the glass-transition temperature of a statistical copolymer is an additive value and the value of  $T_g$  of polymethylphenyl rubber is  $20\text{ }^{\circ}\text{C}$  [15, 16], the expected glass-transition temperature of the modified polymer will not be lower than  $-90\text{ }^{\circ}\text{C}$ . At the same time, some technologies, such as spacecraft engineering or production of freezing equipment for storing vaccines and other unique applications, require significantly lower temperatures. Therefore, the development of such rubbers and elastomers on their basis remains an urgent task.

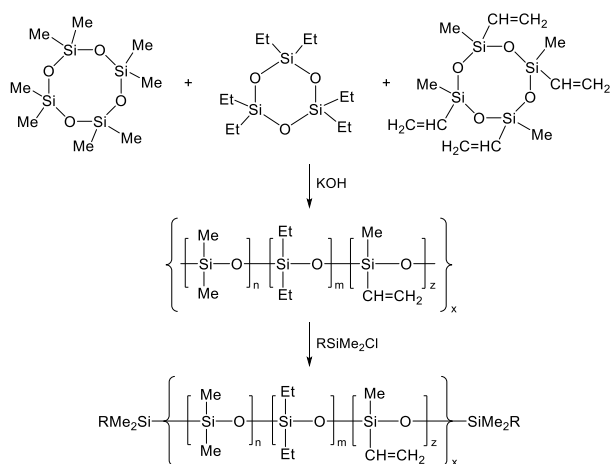
The specificity of silicone production lies in the fact that it is based on a relatively small number of monomers produced on an industrial scale. The choice of other modifying units is limited.

To solve this problem, we turned to the Soviet experience. In the USSR, as is known, there was a wide range of organosilicon monomers, which was not inferior to an analogous line of global manufacturers. At the same time, the USSR was the only country that produced industrially not only methylsiloxanes but also ethylsiloxanes.

It is known that SKTE rubber containing ~8 mol % of diethylsilyl groups displays improved frost resistance owing to the presence of diethylsilyl units in its structure. One of the methods for obtaining SKTE is the copolymerization of dimethylsiloxane and diethylsiloxane cycles in the presence of sulfuric acid, a paste based on aluminum sulfate, and tetramethylammonium hydroxide or potassium silanolate [17, 18]. Unfortunately, the technology of its production featured low reproducibility of the properties and large fluctuations in the content of modifying units, significantly exceeding the acceptable deviations, which led to a considerable deviation in the main frost resistance parameter. Therefore, the goal of this work was to develop a reliable and reproducible method for the synthesis of frost-resistant siloxane rubbers and elastomers on their basis.

## Results and discussion

A siloxane rubber containing diethylsiloxane and methylvinylsiloxane units in its composition was obtained by the anionic copolymerization of octamethylcyclotetrasiloxane ( $D_4(\text{Me})$ ), hexaethylcyclotrisiloxane ( $D_3(\text{Et})$ ), and 1,3,5,7-tetravinyl-1,3,5,7-tetramethylcyclotetrasiloxane in the presence of KOH used as an anionic copolymerization catalyst followed by the neutralization of the resulting copolymer with dimethylvinyl- or trimethylchlorosilane according to Scheme 1.



**Scheme 1.** Copolymer synthesis (R = Me or CH=CH<sub>2</sub>).

The block anionic copolymerization was carried out at 140 °C. The reaction time was 1–1.5 h. The yield of the siloxane rubber ranged from 90 to 93%. In order to avoid structural distortions in the siloxane chain during the further use of the rubber, the terminal functional groups were blocked in a solution of methyl *tert*-butyl ether (MTBE) in the presence of an HCl acceptor.

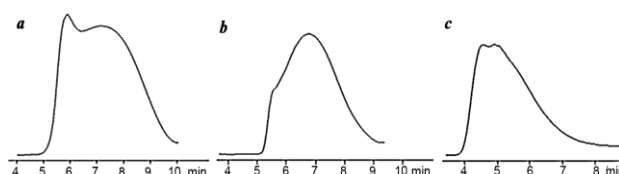
The procedures presented in Scheme 1 were used to obtain the copolymers with the content of dimethyl-, diethyl-, and

methylvinylsiloxane units ranging from 79.00 to 89.99, from 10.00 to 15.00, and from 0.01 to 1.00%, respectively (Table 1).

**Table 1.** Theoretical ratios of the siloxane units in the compositions of the resulting rubber samples

Sample	$[\text{SiMe}_2\text{O}]_m/[\text{SiEt}_2\text{O}]_n/[\text{Si}(\text{MeVin})\text{O}]_z$
1	84.99/15.00/0.01
2	84.97/15.00/0.03
3	84.90/15.00/0.10

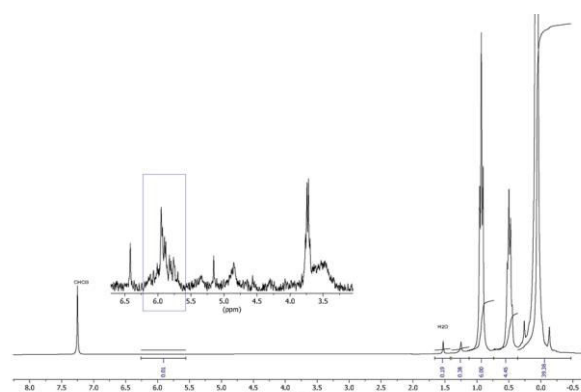
Figure 1 shows the GPC curves for siloxane rubber samples 1–3. According to the GPC data, the molecular weights of the resulting rubbers were above 1000000.



**Figure 1.** GPC curves of samples 1 (a), 2 (b), 3 (c) after distillation of the low-molecular weight products under reduced pressure (Phenogel, 5 μm, 100000 Å, 300 × 4.6 mm).

The low-molecular weight fractions were isolated in small amounts and analyzed by gas liquid chromatography. Their main components appeared to be unreacted octamethylcyclotetrasiloxane as well as its linear and cyclic oligomers. Furthermore, the low-molecular weight fractions also included small amounts of mixed diethylsiloxane derivatives, while methylvinylsiloxane derivatives were present in trace amounts.

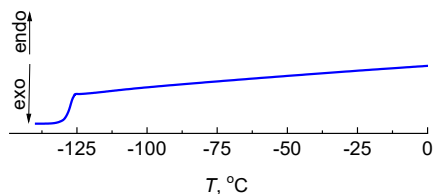
The presence of dimethylsiloxane, diethylsiloxane, and methylvinylsiloxane units in the structures of the resulting siloxane rubbers was confirmed by the <sup>1</sup>H NMR spectroscopic data. For illustration, Fig. 2 shows the <sup>1</sup>H NMR spectrum of sample 2. The <sup>1</sup>H NMR spectroscopic data qualitatively demonstrate the presence of methylvinylsiloxane units in the structure of the siloxane rubber. The ratio of  $[\text{SiMe}_2\text{O}]_m/[\text{SiEt}_2\text{O}]_n$  units in the rubber was ~7/1.



**Figure 2.** <sup>1</sup>H NMR spectrum of the resulting siloxane rubber (sample 2).

According to the results of DSC analysis, the glass-transition temperature of all rubber samples was –129 °C and the crystallization process was effectively suppressed owing to the introduction of diethylsiloxane units into the copolymer

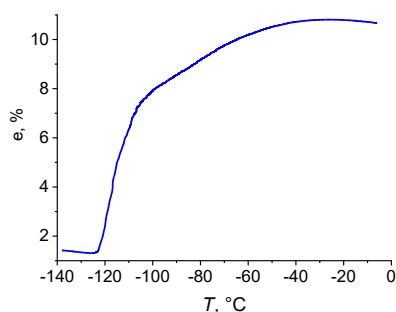
structure. All the samples had similar DSC curves. Figure 3 shows the DSC curve of sample 1 used as a representative example.



**Figure 3.** DSC curve of the resulting siloxane rubber (sample 1).

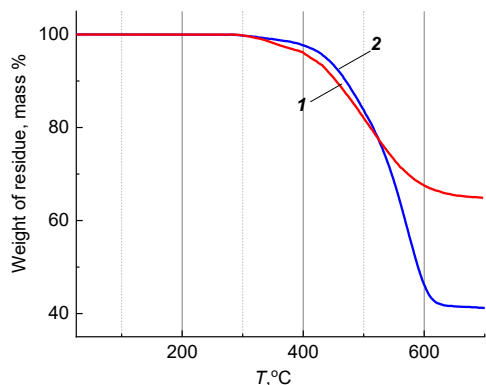
A frost-resistant elastomer was obtained by the vulcanization of the siloxane rubber (sample 1) using 2,4-dichlorobenzoyl peroxide as a radical vulcanization initiator.

According to the TMA data (Fig. 4), the elastomer derived from the siloxane rubber can be used at extremely low temperature ranges.



**Figure 4.** TMA curve of the elastomer based on the resulting frost-resistant siloxane rubber (sample 1).

The resulting siloxane elastomer is thermally stable up to 300 °C (Fig. 5). The temperature that corresponds to 5% weight loss in an argon atmosphere is about 420 °C, and that of 10% weight loss in an argon atmosphere is about 460 °C. The corresponding values in air are 380 °C and ~440 °C, respectively. The carbon residue is 63% in air and 40% in argon.



**Figure 5.** TGA curves of the resulting siloxane elastomer in air (1) and in argon (2) recorded at a heating rate of 10 deg/min.

The resulting frost-resistant elastomer was subjected to mechanical tests. The test samples were blades with a thickness of 2 mm prepared according to the *GOST* (State Standard) 270–75 and arcuate samples with a thickness of 2 mm prepared

according to the *GOST* (State Standard) 262–93. The performed investigations showed that the values of nominal tensile strength, relative elongation at break, and tear resistance were 6.86, 121.20, and 8.00 (N/mm), respectively. Thus, in terms of the main consumer properties, the resulting frost-resistant siloxane elastomer is not inferior to the world analogs, such as Momentive Performance Materials RTV577 Silicone - Commercial Grade Red/Orange, DOW DOWSIL™ 3-6121 Low Temperature Elastomer, and others [19–28].

## Experimental

### General remarks

Hexamethyldisilazane (99%, EKOS-1), KOH (reagent grade, 85%,  $K_2CO_3 \leq 2.0\%$ , water 10–15%), chlorotrimethylsilane (TMCS) (99%, Sigma-Aldrich), dimethylvinylchlorosilane (DMVCS) (97%, Acros Organics), octamethylcyclotetrasiloxane (98%, Acros Organics), 1,3,5,7-tetramethyl-1,3,5,7-tetramethylcyclotetrasiloxane (97%, ABCR), short-chain  $\alpha,\omega$ -dihydroxypolydimethylsiloxanes (ND-8, where  $n = 2-4$ , containing 8.5–13.5 wt % of the OH groups, OAO "Kazanskii zavod SK"), and DCBP (2,4-dichlorobenzoyl peroxide, 50% in silicone oil, NOVIPER DB 50) were purchased from commercial sources and used without further purification.

The organic solvents (hexane, MTBE) were purified prior to use according to the standard procedures [29, 30].

Hexaethylcyclotrisiloxane was obtained by the published procedure [31] and distilled over  $CaH_2$ .

The GPC analysis was performed using the following chromatographic system: LC-10ADvp high-pressure pump (Shimadzu, Japan), SmartlineRI 2300 refractometer detector (KNAUER, Germany), and JETSTREAM 2 PLUS thermostat (KNAUER, Germany). The temperature was  $40 \pm 0.1$  °C, the eluent was toluene + 2% THF, the flow rate was 1.0 mL/min. The analysis was carried out using  $300 \times 7.8$  mm columns with Phenogel sorbent (Phenomenex, USA), 5  $\mu m$ , pore size from 50 to 105 Å; the calibration was performed using Agilent polystyrene standards (USA). The MultiKhrom program for Windows, version 1.6 (Ampersend, Russia) was used for the processing of the resulting chromatograms and calculation of the molecular-mass characteristics.

The  $^1H$  NMR spectra were recorded on a Bruker WP 250 SY spectrometer (Germany). The  $^{13}C$  and  $^{29}Si$  NMR spectra were recorded on a Bruker AVANCE II 300 spectrometer (Germany). The solvent in use was  $CDCl_3$ . The spectra were processed using the ACDLABS program.

The GLC analysis was carried out on a Khromatek-Crystal 5000 chromatograph (Russia) using a katharometer detector, helium carrier gas, columns 2 m  $\times$  3 mm, stationary phase SE-30 (5%) on Chromaton-H-AW. The results were processed using the Chromatek Analyst 2.6 program (Russia).

The DSC studies were conducted on a DSC-822e differential scanning calorimeter (Mettler Toledo, Switzerland) at a heating rate of 10 deg/min.

The TMA measurements were carried out on a TMA/SDTA 2+ LN/600/221 MettlerToledo unit (Switzerland) using a penetrating ceramic rod with a hemispherical tip, 3 mm in diameter, under constant load and heating at a constant

temperature change rate of 10 deg/min.

The TGA analysis was performed on a combined TGA-DSC STAJUPITER 443 F3 unit (NETZSCH, Germany) in air and in an argon atmosphere with a heating rate of 10 deg/min.

The mechanical properties were studied according to the GOST (State Standard) 262–93: *Rubber*. The tear resistance (forked, angular, and sickle-shaped samples) was determined according to the GOST (State Standard) 270–75: *Rubber*. The stress-strain properties were defined according to the GOST (State Standard) 269–66: *Rubber*. The experiments were carried out on GOTECHAI 3000-type tensile testing machines or analogous units that correspond to the GOST (State Standard) 28840–90. The test samples were double-sided blades and angular samples cut from the plates with a thickness of  $\approx 2$  mm.

## Syntheses

### General procedure for the synthesis of siloxane rubbers using the example of the siloxane rubber containing 84.99, 15.00, and 0.01% of dimethyl-, diethyl- and methylvinylsiloxane units.

The copolymer was synthesized by the anionic copolymerization of three organocyclosiloxanes. A round-bottom flask was charged with 255 g (0.87 mol) of octamethylcyclotetrasiloxane, 45 g (0.15 mol) of hexaethylcyclotrisiloxane, 30 mg (8.72 mmol) of 1,3,5,7-tetravinyl-1,3,5,7-tetramethylcyclotetrasiloxane, and 11.7 mg (0.3 mmol) of KOH used as an anionic polymerization catalyst. The reaction was accomplished at 140 °C for 1.5 h and afforded a viscous product. The chain termination was performed by blocking the terminal groups with TMCS or DMVCS in the presence of hexamethyldisilazane used as an HCl acceptor in MTBE. The solvent was removed under reduced pressure. The low-molecular reaction products were removed under vacuum (1 Torr). Yield: 90%.  $^1\text{H NMR}$  ( $\text{CDCl}_3$ ):  $\delta$  0.1 (s,  $\text{SiCH}_3$ ), 0.59 (q,  $\text{SiCH}_2\text{CH}_3$ ), 0.99 (t,  $\text{SiCH}_2\text{CH}_3$ ), 5.9 (q,  $\text{SiCH}_2=\text{CH}_2$ ) ppm. The ratio of the siloxane units  $[\text{SiMe}_2\text{O}]_m/[\text{SiEt}_2\text{O}]_n$  in the resulting rubber was  $\sim 7/1$ .

### General procedure for the synthesis of frost-resistant elastomers.

The synthesis of the frost-resistant elastomer was carried out in two stages:

Stage 1 (mixing of the components): rubber (molecular weight 1000000, 100 g), pyrogenic silica Aerosil 175 (40 g), ND-8 (10 mL), and DCBP (0.8 g).

The rubber was mixed with the components in two stages on rollers at the roller temperature no higher than 33 °C and a roller spacing of  $1 \pm 0.2$  mm.

At the first stage of mixing, the components were introduced gradually as they were rubbed into the rubber, the mixture was cut with a scraper with a working part at least 100 mm wide. The mixture was allowed to homogenize and rest at room temperature for 12 h.

At the second stage, the rubber was mixed with a paste containing 50% of 2,4-dichlorobenzoyl peroxide.

Prior to vulcanization, the rubber mixture was kept at room temperature for at least 6 h, then processed on rollers for 3 min. The roller spacing was increased, and the mixture was derived in the form of sheets with a thickness of 2.1–2.2 mm for the preparation of plates for vulcanization to determine the physical

and mechanical properties and in the roll form (6.4 + 1 mm) for the preparation of washers with a diameter of 50 mm to determine hardness.

The vulcanization was carried out in two stages. At the first stage, the blanks of plates and washers were loaded into appropriate vulcanization molds, preliminarily treated with a lubricant (GOST (State Standard) 13145–67, GOST (State Standard) 19729–74, GOST (State Standard) 20706–75) and heated to a temperature no higher than 40 °C. The rubber mixture was vulcanized at a temperature of  $122 \pm 1$  °C and a pressure per a cell area no less than 3.5 MPa (35 kgf/cm<sup>2</sup>). The process duration was 20 min for plates and 30 min for washers. The vulcanization time was measured from the moment when the press temperature reached  $122 \pm 1$  °C. At the end of vulcanization, the pressure was removed, the molds were unloaded from the press, the samples were taken out of the molds and transferred to the second stage of vulcanization. The rest time of the samples after the first stage of vulcanization was 15 min at room temperature.

At the second stage of vulcanization, the samples in the form of plates and washers were placed on metal pallets at such a distance that they did not touch each other. During a time period of 1 h, the temperature in the thermostat was uniformly raised to  $200 \pm 2$  °C. Then the plates and washers were kept at this temperature for 6 h. The nominal tensile strength and relative elongation at break were determined for the samples of type I with a thickness of  $2 \pm 0.2$  mm according to the GOST (State Standard) 270–75 and 269–66.

## Conclusions

The anionic block copolymerization of  $\text{D}_4(\text{Me})$ ,  $\text{D}_3(\text{Et})$ , and 1,3,5,7-tetravinyl-1,3,5,7-tetramethylcyclotetrasiloxane in the presence of KOH used as an anionic copolymerization catalyst is a more promising method for obtaining frost-resistant rubbers and elastomers than the previously published approaches since this method is simpler and more technologically advanced. The prospects of this method are also associated with the possibility of controlling the chemical composition of a rubber by varying the content of diethylsiloxane and methylvinylsiloxane units in the copolymer structure. At the same time, the introduction of diethylsiloxane units into the structure of PDMS enables the reduction of the glass-transition temperature of the rubber down to  $-129$  °C and suppresses the crystallization process without deteriorating its high-temperature characteristics. The suggested method allows for a significant expansion of the operating temperature range of the final product. The resulting frost-resistant elastomer retained its performance characteristics upon temperature decrease down to  $-123$  °C and was not inferior to the world analogs in terms of the nominal tensile strength and the temperature dependence of the material strain.

## Acknowledgements

This work was supported by the Russian Science Foundation, project no. 21-73-30030.

The NMR, GPC, GLC and TGA studies were performed at the Collaborative Research Center "Center for Polymer Research" of ISPM RAS supported by the Ministry of Science

and Higher Education of the Russian Federation, topic no. FFMS-2021-0004.

The DSC and TMA experiments were carried out at the Center for Molecular Composition Studies of INEOS RAS with financial support from the Ministry of Science and Higher Education of the Russian Federation, agreement no. 075-00697-22-00.

## Corresponding author

\* E-mail: obrezkova@list.ru. Tel: +7(495)332-5833 (M. A. Obrezkova)

## References

1. A. A. Anisimov, A. V. Zaitsev, V. A. Ol'shevskaya, M. I. Buzin, V. G. Vasil'ev, O. I. Shchegolikhina, A. M. Muzafarov, *INEOS OPEN*, **2018**, *1*, 71–84. DOI: 10.32931/101806r
2. N. V. Belozherov, *TU (Specifications) 2294-054-05766764-2003: Silicone Rubber SKTFV-803, Rubber Technology*, **1964** [in Russian].
3. F. M. Palyutin, G. A. Mikhailova, V. P. Kakurina, F. K. Lutfullina, V. Ya. Kalmykova, *Vestnik Kazan. Tekhnol. Univ.*, **2006**, *2*, 228–231.
4. L. Liu, S. Yang, Z. Zhang, Q. Wang, Z. Xie, *J. Polym. Sci., Part A: Polym. Chem.*, **2003**, *41*, 2722–2730. DOI: 10.1002/pola.10822
5. P. R. Dvornic, in: *Silicon-Containing Polymers. The Science and Technology of Their Synthesis and Applications*, R. G. Jones, W. Ando, J. Chojnowski (Eds.), Springer, Dordrecht, **2000**, pp. 185–212. DOI: 10.1007/978-94-011-3939-7\_7
6. C. L. Beatty, F. E. Karasz, *J. Polym. Sci., Polym. Phys. Ed.*, **1975**, *13*, 971–975. DOI: 10.1002/pol.1975.180130509
7. C. L. Beatty, J. M. Pochan, M. F. Froix, D. D. Hinman, *Macromolecules*, **1975**, *8*, 547–551. DOI: 10.1021/ma60046a031
8. P. R. Dvornic, R. W. Lenz, *High Temperature Siloxane Elastomers*, Huthig & Wepf, Heidelberg, **1990**.
9. P. A. Tikhonov, N. G. Vasilenko, A. M. Muzafarov, *Dokl. Chem.*, **2021**, *496*, 1–17. DOI: 10.1134/S001250082101002X
10. P. A. Tikhonov, N. G. Vasilenko, M. O. Gallyamov, G. V. Cherkaev, V. G. Vasil'ev, N. V. Demchenko, M. I. Buzin, S. G. Vasil'ev, A. M. Muzafarov, *Molecules*, **2021**, *26*, 3280. DOI: 10.3390/molecules26113280
11. Yu. S. Vysochinskaya, A. A. Anisimov, A. S. Peregudov, A. S. Dubovik, V. N. Orlov, Yu. N. Malakhova, A. A. Stupnikov, M. I. Buzin, G. G. Nikiforova, V. G. Vasil'ev, O. I. Shchegolikhina, A. M. Muzafarov, *J. Polym. Sci., Part A: Polym. Chem.*, **2019**, *57*, 1233–1246. DOI: 10.1002/pola.29380
12. Yu. S. Dyuzhikova, A. A. Anisimov, A. S. Peregudov, M. I. Buzin, G. G. Nikiforova, V. G. Vasil'ev, S. A. Kostrov, A. I. Buzin, A. A. Stupnikov, Yu. N. Malakhova, O. I. Shchegolikhina, A. M. Muzafarov, *Polymers*, **2022**, *14*, 285. DOI: 10.3390/polym14020285
13. S. V. Reznichenko, Yu. L. Morozova, *Handbook of a Rubber-Industry Worker, Part 1. Rubbers and Ingredients*, Moscow, Publ. Center "Tekhinform" of International Academy of Information, **2012** [in Russian].
14. S. V. Reznichenko, Yu. L. Morozova, *Handbook of a Rubber-Industry Worker, Part 2. Rubbers and Rubber Products*, Moscow, Publ. Center "Tekhinform" of International Academy of Information, **2012** [in Russian].
15. *Polymer Data Handbook*, Oxford Univ. Press, New York, **1999**.
16. B. Momper, T. Wagner, U. Maschke, M. Ballauff, E. W. Fischer, *Polym. Commun.*, **1990**, *31*, 186.
17. S. N. Borisov, I. K. Stavitskii, A. V. Karlin, I. A. Malysheva, USSR Inventor's Certificate no. 132405, **1960**.
18. S. N. Borisov, I. K. Stavitskii, A. V. Karlin, I. A. Malysheva, *Polym. Sci. U. S. S. R.*, **1962**, *3*, 950–956. DOI: 10.1016/0032-3950(62)90177-6
19. <https://www.momentive.com/en-us/categories/adhesives-and-sealants/rtv511-rtv560-and-rtv577>
20. [https://www.rubbercal.com/sheet-rubber/silicone-rubber/?gclid=CjwKCAjwrvv3BRAJEiwAhwOdM-1JYYDTadwtEOtkk-cyOaKeIf1fMtctOXC9TtEahgsYx2q9Ud35cRoCpQ0QAvD\\_BwE](https://www.rubbercal.com/sheet-rubber/silicone-rubber/?gclid=CjwKCAjwrvv3BRAJEiwAhwOdM-1JYYDTadwtEOtkk-cyOaKeIf1fMtctOXC9TtEahgsYx2q9Ud35cRoCpQ0QAvD_BwE)
21. [https://www.rubbercal.com/sheet-rubber/silicone-rubber/?gclid=CjwKCAjwrvv3BRAJEiwAhwOdM-1JYYDTadwtEOtkk-cyOaKeIf1fMtctOXC9TtEahgsYx2q9Ud35cRoCpQ0QAvD\\_BwE](https://www.rubbercal.com/sheet-rubber/silicone-rubber/?gclid=CjwKCAjwrvv3BRAJEiwAhwOdM-1JYYDTadwtEOtkk-cyOaKeIf1fMtctOXC9TtEahgsYx2q9Ud35cRoCpQ0QAvD_BwE)
22. <https://www.sspinc.com/products/detail/17/SSP-1405-L-Silicone-Lubricant/>
23. <https://hollandshielding.com/Silicone-shielding-elastomers>
24. [https://www.shinetsusilicone-global.com/catalog/pdf/rubber;e.pdfhttp://www.shinetsusilicone-global.com/products/type/rubb\\_comp/index.shtml](https://www.shinetsusilicone-global.com/catalog/pdf/rubber;e.pdfhttp://www.shinetsusilicone-global.com/products/type/rubb_comp/index.shtml)
25. <https://www.wacker.com/h/en-us/c/elastosil-r-49055-oh/p/000005558>
26. <https://acc-silicones.com/products/encapsulants/SE2010>
27. <https://www.epoxies.com/bulletinsearch/?tech=20-1615>
28. <https://www.dow.com/en-us/document-viewer.html?randomVar=4043875394637814590&docPath=/content/dam/dcc/documents/en-us/productdatasheet/11/11-12/11-1254-01-dowsil-3-6121-low-temperature-elastomer.pdf>
29. A. J. Gordon, R. F. Ford, *The Chemist's Companion*, Wiley, New York, London, Sydney, Toronto, **1972**.
30. W. L. F. Armarego, D. D. Perrin, *Purification of Laboratory Chemicals, 4th ed.*, Butterworth-Heinemann, **1996**.
31. G. J. J. Out, H.-A. Klok, M. Möller, D. Oelfin, *Macromol. Chem. Phys.*, **1995**, *196*, 195–210. DOI: 10.1002/macp.1995.021960113

This article is licensed under a Creative Commons Attribution-NonCommercial 4.0 International Licence.

