ISSN 2075-8545 (online)

Nanotechnologies in construction
Нанотехнологии в строительстве

2026; 18 (5):
601–608

Nanobuild.ru

THE RESULTS OF THE SPECIALISTS' AND SCIENTISTS' RESEARCHES

Original article
https://doi.org/10.15828/2075-8545-2026-18-5-601-608

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Assessment of the potential application of thermoplastic polymers for insulating the electrodes of high-temperature cartridge-type electric heaters

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ABSTRACT

Introduction. Tubular electric heaters are widely used in industrial and domestic heating applications. Structurally, tubular electric heaters consist of a metal shell housing a heating element, with the space between them filled with a high-temperature, heat-conducting dielectric material. A tubular electric heater is divided into several zones: the active (heating) zone, the cold zone (contact terminal zone), and the transition zone. The "cold" sections of the tubular electric heater, where the contact rods connected to the terminal wires are located, are the most critical in terms of electrical safety and durability. This zone requires reliable electrical insulation, sealing from the external environment (moisture, corrosive environments, dust, aggressive vapors), and mechanical fixation of the current-carrying elements. The aim of this study was to develop and optimize the composition of a sealing material for the cold section of a tubular electric heater. **Materials and Methods.** To achieve this goal, a series of pilot samples of sealing materials for protective insulating coatings were manufactured by modifying their compositional components: the polymer base, plasticizer, and filler. Samples of sealing materials for the cold section of tubular electric heaters were subjected to a comprehensive evaluation of their adhesive strength, oil-and-petrol resistance, dielectric and mechanical properties, and chemical resistance. **Results.** The paper presents an analysis of the feasibility of using an insulating nanomaterial for the cold section of a tubular electric heater. The results of a study of materials with various compositions, including Ammerheim Phenol Epoxy phenol-epoxy coating, T-111 epoxy resin, F-4D fluoroplastic suspension with nanoscale particles, one-component silicone sealant, ethyl cellulose, VIKSINT PK-68 organosilicon rubber, and SEDM-6 epoxy resin, showed that the most promising material for sealing the "cold" section of a tubular electric heater is F-4D fluoroplastic, which exhibits unique chemical resistance to gasoline, oils, and aggressive environments, a wide operating temperature range (from –190 to 250 °C), and excellent dielectric properties. **Conclusion.** Based on the results of the tests, fluoroplastic F-4D was selected as the sealing dielectric material for the "cold" section of the cartridge electric heater. This material possesses the necessary properties for operation: heat resistance, oil-and- petrol resistance, dielectric strength, high ductility, and chemical resistance. However, the fluoroplastic F-4D-based composition requires additional modification to improve adhesion to the metal surface of the tubular electric heater.

KEYWORDS: tubular electric heater, dielectric resistance, heat resistance, oil-and-petrol resistance, chemical resistance, fluoroplastic

SOURCES OF FUNDING FOR THE SCIENTIFIC WORK THAT RESULTED IN THE PUBLICATION: This work was conducted as part of the Strategic Project "New technologies, technical, and intelligent systems in mechanical engineering" of the Ufa State Petroleum Technological University Development Program for 2021–2030 in accordance with the Priority 2030 Strategic Academic Leadership Program.

ACKNOWLEDGEMENTS: The authors are grateful for the financial support of this project.

FOR CITATION:
Latypov O.R., Kim K.V., Lukyanov V.V., Latypova D.R., Daminev R.R., Khusnutdinova A.Z. Assessment of the potential application of thermoplastic polymers for insulating the electrodes of high-temperature cartridge-type electric heaters. *Nanotechnologies in Construction*. 2026;18(5):601–608. https://doi.org/10.15828/2075-8545-2026-18-5-601-608. – EDN: SOFXUR.

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ISSN 2075-8545 (online)

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Nanobuild.ru

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Анализ возможности применения термопластичных полимеров для изоляции электродов высокотемпературных патронных электрических нагревателей

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АННОТАЦИЯ

Введение. Трубчатые электронагреватели нашли широкое применение в промышленных и бытовых нагревательных устройствах. Конструктивно трубчатые электронагреватели представляет собой металлическую оболочку, внутри которой расположен нагревательный элемент, а пространство между ними заполнено высокотемпературным теплопроводящим диэлектрическим материалом. В конструкции трубчатого электронагревателя выделяют несколько зон: активную (нагревательную), холодную зону (зону вывода контактов) и переходную область. Наиболее ответственными с точки зрения электрической безопасности и долговечности являются «холодные» части трубчатого электронагревателя, где располагаются контактные стержни, соединенные с выводными проводами. Именно в этой зоне необходимо обеспечить надежную электроизоляцию, герметизацию от внешней среды (влаги, коррозионной среды, пыли, агрессивных паров) и механическую фиксацию токоведущих элементов. Целью работы являлась разработка и оптимизация состава герметизирующего материала для холодной части трубчатого электронагревателя. **Материалы и методы.** Для достижения цели были изготовлены серии опытных образцов герметизирующих материалов для защитного изоляционного покрытия путем модифицирования их компонентов состава: полимерной основы, пластификатора и наполнителя. Образцы из герметизирующих материалов для холодной части трубчатого электронагревателя подвергли комплексной оценке на их адгезионную прочность, маслобензостойкость, диэлектрические и механические характеристики, а также химическую стойкость. **Результаты.** В работе приведен анализ возможности применения изолирующего наноматериала на холодную часть трубчатого электронагревателя. Результаты исследования материалов различных составов: фенол-эпоксидного покрытия «Аммерхайм Фенол Эпокси», эпоксидной смолы Т-111, фторопластовой суспензии Ф-4Д с наноразмерными частицами, однокомпонентного силиконового герметика, этилцеллюлозы, кремнийорганического каучука ВИКСИНТ ПК-68, эпоксидной смолы СЭДМ-6 – показали, что наиболее перспективными материалами для герметизации «холодной» части трубчатого электронагревателя является фторопласт Ф-4Д, который обладает уникальной химической стойкостью к бензину, маслам и агрессивным средам, широким диапазоном рабочих температур (от –190 до 250 °С) и превосходными диэлектрическими свойствами. **Заключение.** В результате проведенных испытаний выбран герметизирующий диэлектрический материал фторопласт Ф-4Д для «холодной» части патронного электрического нагревателя. Этот материал обладает необходимыми для эксплуатации свойствами: термостойкостью, маслобензостойкостью, диэлектрической прочностью, имеет высокую пластичность и химическую стойкость. Однако композиция на основе фторопласт Ф-4Д требует дополнительной модификации для повышения адгезии к металлической поверхности трубчатого электронагревателя.

КЛЮЧЕВЫЕ СЛОВА: трубчатый электронагреватель, диэлектрическая стойкость, термостойкость, маслобензостойкость, химическая стойкость, фторопласт

ИСТОЧНИКИ ФИНАНСИРОВАНИЯ НАУЧНОЙ РАБОТЫ, РЕЗУЛЬТАТОМ КОТОРОЙ СТАЛА ПУБЛИКАЦИЯ: Работа проводилась в рамках реализации Стратегического проекта «Новые технологии, технические и интеллектуальные системы в машиностроении» программы развития ФГБОУ ВО «Уфимский государственный нефтяной технический университет» на 2021-2030 годы в соответствии с программой стратегического академического лидерства «Приоритет 2030».

БЛАГОДАРНОСТИ: Авторы выражают благодарность за финансовую поддержку проекта.

ДЛЯ ЦИТИРОВАНИЯ:

Латыпов О.Р., Ким К.В., Лукьянов В.В., Латыпова Д.Р., Даминев Р.Р., Хуснутдинова А.З. Анализ возможности применения термопластичных полимеров для изоляции электродов высокотемпературных патронных электрических нагревателей. *Нанотехнологии в строительстве*. 2026;18(5):601–608. https://doi.org/10.15828/2075-8545-2026-18-5-601-608. – EDN: SOFXUR.

ISSN 2075-8545 (online)

INTRODUCTION

Cartridge tubular electric heaters are widely used for heating casting molds and press forms, as well as various liquids, such as water, fats and oils, and acid and alkali solutions. These products serve as components in industrial installations and household heating appliances [1–3]. A promising area of application may be the oil and gas production industry. However, oil field environments are characterized by high aggressiveness. The corrosive aggressiveness of oil field environments is caused by the presence of dissolved acidic gases (CO_2, O_2 and H_2S), abrasive particles, basic salt ions (Mg^{2+}, Ca^{2+}, Na^+, SO_4^{2-}, Cl^-), water-soluble mineral and organic acids and bases, as well as the presence of anaerobic and aerobic microorganisms, the metabolic products of which provoke microbiological corrosion of metal and biofouling [4–7]. The cold section of a tubular electric heater is an unheated section near the terminals of electrical wires, the length of which varies depending on the heater design, and the cross-section and diameter of the resistive heating element are determined based on the specific power permissible for the material under the given operating conditions [2]. The sealing zone of the cold section is critical in terms of thermal and chemical effects. The destruction of the sealed layer and subsequent diffusion of moisture contributes to the saturation of the heat-conducting insulating material of the inner part of the cartridge electric heater, which can lead to its destruction and electrical breakdown on the housing [8].

Electrical strength and high insulation resistance are fundamental to ensuring electrical safety when operating a cartridge heater. Cold insulation resistance must be at least 0.5 megohms at 500 VDC. Leakage current, in turn, is standardized to no more than 0.75 mA/kW at 127–380 V, 50 Hz. The recommended test voltage for polymer insulation can reach 2500 V. Insulation resistance must be at least 20 megohms. However, increasing temperature can reduce the resistance of the insulating material, so heat resistance is also important – this is the material's ability to withstand elevated temperatures without deteriorating its properties for a period equal to its normal service life [9]. Insulation resistance depends on temperature, electrical and mechanical stress, vibration, environmental aggressiveness, chemical influences, and humidity [10]. To insulate the cold section of the heater, it is necessary to use insulating materials of heat resistance class F (155 °C) or H (180 °C). Moreover, the product must withstand short-term overheating up to 200 °C. In addition to high-temperature resistance, the insulation must maintain elasticity and integrity under cyclic temperature changes and not cause cracking of the coating.

Contact between the cold section of a cartridge heater and hydrocarbon liquids (oil, gasoline, and lubricants) is inevitable when operating heaters in the oil industry. Therefore, the insulation material for the cold section of a cartridge heater must be sufficiently oil-and-petrol resistance.

In the oil and gas industry, wire insulation must withstand a range of aggressive factors: natural gas and its components, hydrogen sulfide (H_2S), carbon dioxide (CO_2), formation waters with a high salt content, acids and alkalis used in well treatment, solvents used in cleaning equipment, as well as other process fluids [5–6].

In this regard, specific requirements are imposed on the insulating material for the cold section of the cartridge electric heater: a wide operating temperature range: from –60 °C to +180 °C; resistance to hydrocarbon environments (oil and gasoline resistance); high dielectric properties; good adhesion to metal substrates; chemical resistance to aggressive environments – acidic gases, salts, acids and alkalis.

MATERIALS AND RESEARCH METHODS

Polymer compositions that are already in use or are considered the most promising for the operation of the cold section of a cartridge electric heater in aggressive conditions were selected as test objects [11–14].

Ammerheim Phenol Epoxy coating is a two-component phenol-epoxy composition based on novolac resin. According to the manufacturer's technical documentation, the coating is designed for the anti-corrosion protection of metal structures operating at temperatures up to 220 °C. It is resistant to sudden temperature changes and chemically resistant to hydrocarbons, acids, and alkalis.

T-111 resin is an epoxy resin modified with polyorganosiloxane. It is designed for the production of heat-resistant adhesives, in particular K-400 adhesive, which operates in temperatures ranging from –196 °C to 400 °C for short periods and for up to 1000 hours at 200 °C.

SDM-6 epoxy resin, which is a component of K-300-61 adhesive, can be used in temperatures ranging from –196 °C to 300 °C for 1 minute, and at 200 °C for 1000 hours.

Ethyl cellulose is a cellulose derivative in which some hydroxyl groups are replaced by ethyl groups. It forms strong, durable, and elastic films. It has low hygroscopicity. It is compatible with many plasticizers, resins, and oils.

A one-component silicone sealant designed for sealing, bonding, and sealing joints and components, heating panels, and other elements exposed to high temperatures. It features excellent adhesion to most building materials. It offers high performance characteristics: it maintains elasticity under continuous thermal loads of up to 300 °C and is non-corrosive to metals.

Fluoroplast-4D is a product of tetrafluoroethylene polymerization, produced in an aqueous environment under pressure. Fluoroplast has high dielectric properties

ISSN 2075-8545 (online)

and is resistant to aggressive environments. The operating temperature of fluoroplastic films ranges from –60 °C to 250 °C.

VIKSINT PK-68 organosilicon rubber is an organosilicon compound designed to protect electronic and radio-technical equipment operating for extended periods in air and high-humidity conditions at temperatures ranging from –60 °C to 200 °C. The compound's softness and elasticity make it suitable for sealing ferrite and permalloy components.

To produce free-standing films (for tensile testing and oil and petrol resistance), fluoroplastic-4 plates measuring 200×200×3 mm, according to GOST 10007-80, were used. The film was separated from the fluoroplastic mechanically after complete curing.

For adhesion testing, we used 50×50×2 mm plates made of 12Kh18N10T corrosion-resistant steel. Before coating application, the plate surface was sanded with 120–150 μm abrasive paper to achieve a roughness of Ra 1.6–3.2 μm. A two-stage degreasing process was then performed: first with acetone, then with isopropyl alcohol. The plates were wiped with lint-free cloths, changing them at each stage.

Oil-and-petrol resistance tests were conducted on the materials using a methodology adapted from GOST 12020-2018. Thickness swelling and mass changes of the material samples were calculated. For this purpose, 50×50 mm specimens were cut from loose films of the material, their thickness was measured at five points with a micrometer to an accuracy of 0.01 mm, and weighed on an analytical balance. The specimens were completely immersed in gasoline at a temperature of (22±2) °C for periods of 1, 3, 24, 48, and 196 hours. After removal, the specimens were blotted with filter paper, re-weighed, and their thickness was measured. The appearance of cracks, bubbles, cloudiness, delamination, and other defects was also visually noted, and the change in area due to warping was determined.

Adhesion was tested using the normal pull-off method according to GOST 32299-2025 (ISO 4624:2023) on a REM-U-A universal testing machine (Russia) with a maximum load of 50 kN. The loading rate was 1 mm/min. Steel cylindrical caps were glued to the coating with KD-19 epoxy adhesive. The adhesive was cured for 24 hours at a temperature of (22±5) °C in fixtures for centering the cylindrical caps to the coating. After curing, the sample was secured in the machine grips and loaded until failure. The failure mode was assessed visually: adhesive (peeling off from the substrate), cohesive (rupture within the coating), mixed (peeling off the cap from the coating or a combination of both).

Tensile properties were determined in accordance with GOST 11262-2017. The method involves stretching a specimen at a specified strain rate until failure, determining the ultimate strength and relative elongation. Type 2 (blade) specimens were cut from loose films in accordance with GOST 11262-2017. Tests were conducted on a REM-U-A universal testing machine (Russia) at a temperature of 23±2 °C. The specimen was clamped in wedge or screw grips of the machine such that its longitudinal axis coincided with the loading direction, and the working part was positioned between the grips without distortion. During testing, the load-displacement diagram was automatically recorded using the built-in software. At least three specimens for each composition were tested. The final result was taken as the arithmetic mean; the measurement error according to GOST 11262-2017 for the load should not exceed 1% of the measured value.

The thermal stability of the coatings was assessed by annealing in a KS-18 furnace (Russia) at elevated temperatures. The annealing temperatures were 150, 180, and 200 °C. The coatings were held at these temperatures for 1 hour, and cooled in air at room temperature until completely cooled. Color change, cracks, and warpage of the samples were assessed.

The volume and surface electrical resistance of the insulating coatings were measured with a megohmmeter. The voltage was applied for 60 seconds – the time required for the current to reach a steady state due to polarization processes in the dielectric. The steady-state resistance was recorded.

RESULTS AND DISCUSSION

Due to the promising use of cartridge heaters in the oil and gas industry, oil and gasoline resistance tests were initially conducted. The worst results were observed for ethyl cellulose films. During the preparation and application of the composition to steel samples, a highly porous structure was observed due to incomplete dissolution of the ethyl cellulose powder in the ketone solvent, leading to particle agglomeration and clump formation. The experiment revealed that the developed porosity of the resulting film resulted in its poor barrier properties, specifically, a lack of oil-and-petrol resistance.

Testing of the coating formed using VIKSINT PK-68 organosilicon rubber also revealed its unsuitability for hydrocarbon-containing environments. When a steel plate coated with this coating was immersed in gasoline, swelling resulted in adhesion failure and subsequent peeling.

SEDM-6 and T-11 epoxy resins tested in gasoline for 24 hours showed satisfactory results: swelling resulted in a weight increase of 18 to 20%.

Test results of a single-component silicone sealant showed that the material is resistant to hydrocarbon environments, with no visible signs of degradation, cracking, or adhesion loss. Therefore, this silicone sealant has been established to have sufficient oil-and-petrol resistance for use in contact with gasoline and oils.

ISSN 2075-8545 (online)

The two-component phenol-epoxy coating "Ammerheim Phenol Epoxy" demonstrated the best results. Visual and instrumental analysis revealed no noticeable changes in the linear dimensions of the sample (no swelling). After 96 hours of exposure to gasoline, the coating's adhesion to the substrate remained unchanged, with no signs of delamination or degradation.

Test results of a fluoroplastic coating made from F-4D suspension showed that fluoroplastic exhibits virtually no interaction with hydrocarbons. No visible surface changes, warping, or loss of transparency were observed. The films remained flexible and elastic.

Thus, VIKSINT PK-68 materials, one-component silicone sealant, SEDM-6 and T-11 epoxy resins, Ammerheim Phenol Epoxy phenol-epoxy coating, and F-4D fluoroplastic passed the oil-and-petrol resistance tests.

Next, adhesion strength tests were conducted. Table 1 summarizes the test results for the materials under consideration.

It was noted that all test samples exhibited cohesive or mixed peel strength, indicating adequate adhesion to the metal surface. However, even with the use of adhesive underlayers, the fluoroplastic coating does not achieve the adhesion strength typical of phenolic epoxy materials (8–10 MPa) and remains susceptible to failure during multilayer application (Fig. 1).

The next test involved stretching the insulating films to assess their strength properties. Films made from Ammerheim Phenol Epoxy demonstrated a tensile strength of (10±1) MPa at a relative elongation of 30–33%. This level of strength is sufficient to prevent the coating from breaking when the heater is pressed into the mounting hole. An elongation of 30% indicates moderate ductility –

Table 1. Adhesive strength of coatings to a metal substrate

	Ammerheim Phenol Epoxy	Suspension F-4D with nanoscale particles	Primer + F-4D suspension with nanoscale particles	Ammerheim Phenol Epoxy + T-111 Epoxy Resin
Max. load, N	8198 ± 1	716 ± 1	1807 ± 1	6476 ± 1
Max. deformation, mm	4 ± 1	6 ± 1	4 ± 1	6 ± 1
Ultimate tensile strength, MPa	8 ± 1	1± 1	3 ± 1	6 ± 1
Nature of separation	mixed	cohesive	cohesive	mixed

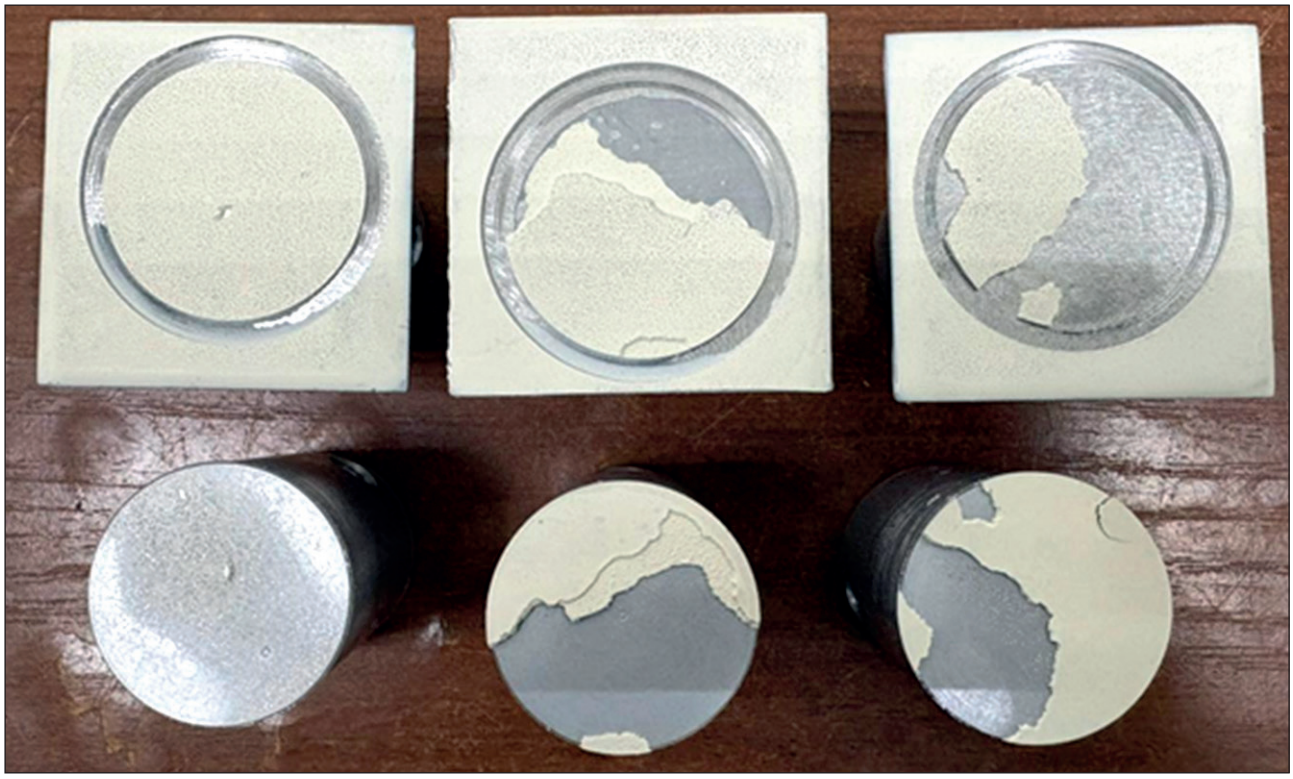

Fig. 1. Cohesive-adhesive peel strength of Ammerheim Phenol Epoxy films + T-111 epoxy resin after testing

ISSN 2075-8545 (online)

the material can be deformed without cracking – but is not highly elastic, which may limit its use in conditions with alternating temperatures.

To assess resistance to elevated temperatures, the coatings were briefly heat-treated to 300 °C. It was found that heating the Ammerheim Phenol Epoxy film to 180 °C and above resulted in irreversible embrittlement. For this material, with the addition of 5–10% plasticizer, heating resulted in a loss of ductility and the appearance of microcracks on the surface.

Films made from T-111 resin exhibited significantly lower strength – (4±1) MPa – but elongation at break reached 49–52%. This is typical behavior for epoxy resins with siloxane modification: they become soft and ductile, but lose strength.

The tensile strength of films made from Ammerheim Phenol Epoxy and T-111 epoxy resin was (6±1) MPa, and the relative elongation was 70.8%. Compared to pure Ammerheim Phenol Epoxy, the strength decreased by approximately 25%, while elasticity more than doubled. This combination of properties is optimal for coatings operating under alternating temperatures: the highly elastic film will follow the deformations of the metal shell without cracking.

Based on the results of measurements and visual inspection of fluoroplast-4 samples, it was established that the material retains its functionality up to 250 °C, and short-term heating up to 300 °C, which allows this limit to be considered acceptable for short-term operating modes (Fig. 2).

One of the key requirements for the insulating material of the "cold" section of a cartridge heater is high electrical resistance, ensuring safe operation at voltages up to 2500 V. According to industry standards, the insulation resistance in the cold state must be at least 1 megohm. The test results are presented in Table 2.

All materials tested showed high insulation resistance, significantly exceeding the required values.

Fig. 2. The appearance of the fluoroplastic-4 coating after heat treatment

CONCLUSION

During the selection of an insulating material for the cold section of a tubular electric cartridge heater, experimental studies were conducted on the following materials: Ammerheim Phenol Epoxy phenol-epoxy coating, T-111 epoxy resin, F-4D fluoroplastic suspension, one-component silicone sealant, ethyl cellulose, VIKSINT PC-68 organosilicon rubber, and SEDM-6 epoxy resin. The experimental results showed:

1.Ammerheim Phenol Epoxy coating exhibits strong adhesion to metal substrates (8–10 MPa), high oil and petrol resistance, high electrical resistance (greater than 2.5 TOhms at 2500 V), and heat resistance up to 200 °C. Based on its combined properties, Ammerheim Phenol Epoxy is recognized as the most balanced material for insulating the cold section of cartridge heaters.

2.T-111 resin demonstrated high elasticity (elongation up to 70%), good dielectric properties (11.57 GOhm), and resistance to short-term overheating up to 400 °C. The main drawback was the difficulty of forming a continuous coating on a metal substrate. However, due to its high elasticity and heat resistance, it can be used as a component in composite compounds.

3.Fluoroplastic F-4D exhibits exceptional chemical resistance to gasoline, oils, and aggressive environments,

Table 2. Results of electrical resistance measurements

Material	Measured resistance, Ohm
Ammerheim Phenol Epoxy	$>2.5 \cdot 10^{12}$ (> 2.5 TOhm)
T-111 Epoxy Resin	$1.157 \cdot 10^{10}$ (11.57 GOhm)
Ammerheim Phenol Epoxy + T-111 Epoxy Resin	$2.3 \cdot 10^{12}$ (2.3 TOhm)
Fluoroplastic F-4D	$>2.5 \cdot 10^{12}$ (> 2.5 TOhm)
One-Component Silicone Sealant	$>2.5 \cdot 10^{12}$ (> 2.5 TOhm)
VIKSINT PK-68 Organosilicon Rubber	$>2.5 \cdot 10^{12}$ (> 2.5 TOhm)

ISSN 2075-8545 (online)

a wide operating temperature range (from –190 °C to +250 °C), and excellent dielectric properties. However, poor adhesion to metal surfaces and cracking during multilayer baking were noted. The use of a primer based on chromium oxide and phosphoric acid increased adhesion to 1.1 MPa, but this is insufficient for direct application to a cold surface. Nevertheless, the material itself is considered promising with further optimization of the adhesive sublayers.

4. This one-component silicone sealant has demonstrated good heat resistance (up to 300 °C) and oil-and-petrol resistance. Silicone sealants maintain their functionality over a wide temperature range and are resistant to hydrocarbons, making them suitable for cold-side insulation, provided adhesion is improved.

The most suitable of the materials studied is fluoroplastic F-4D. It possesses a combination of properties (heat resistance, oil-and-petrol resistance, and dielectric strength) that make it suitable for further development as an insulating coating for the cold section of cartridge heaters.

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ISSN 2075-8545 (online)

ADDITIONAL INFORMATION

The authors declare that generative artificial intelligence (AI) and AI-based technologies were not used in the preparation of this article.

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Vasily V. Lukyanov – methodology development, provision of resources (equipment, materials), data analysis, review and editing.

Dina R. Latypova – methodology development, conducting experiments, validation of results, drafting of the manuscript, review and editing.

Rustem R. Daminev – project administration, provision of resources, scientific supervision, review and editing.

Aliyana Z. Khusnutdinova – conducting experiments, data collection, visualization, preparation of illustrations.

The authors declare no conflicts of interest.

The article was submitted 04.07.2026; approved after reviewing 03.10.2026; accepted for publication 09.10.2026.