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Long-Term Performance Degradation of Polyurethane Foam Fillers in Military Aircraft Fuel Tanks

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Abstract:

Military aircraft fuel tanks are equipped with channel fillers made of elastic porous polymeric materials that are used to prevent explosions. Exposure to aviation fuel alters the morphological structure of the tank filler. To assess the behavior of the polymer material under fire conditions, three samples of polyurethane foam filler (new, exposed to fuel for 5 years, and for 10 years) for heat resistance and operational reliability were tested. The results confirmed that aging affects the reliability and heat resistance of the filler. Given the critical role of these fillers in military aircraft, ensuring their long-term performance is essential for operational safety. Based on the results, recommendations have been developed to enhance the operational performance of aircraft fuel tank fillers.

Keywords:

fuel tank, foam filler, thermal stability, degradation

1 Introduction

The continued operation of aging military aircraft has brought increased attention to the reliability and longevity of their critical systems [1-6]. This issue is particularly relevant for Ukraine, where military aircraft such as the Su-27 and MiG-29 – many of which have been in service since the 1990s – remain in active use. Ensuring the airworthiness and operational safety of these aircraft is a national priority, especially under the current geopolitical conditions. A key aspect of maintaining aircraft perfor-

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mance involves assessing the long-term degradation of onboard systems, including fuel tank components.

Fuel tanks in military aircraft are often equipped with polyurethane (PU) foam fillers designed to mitigate explosion risks by suppressing static electricity and dampening fuel sloshing. However, extended exposure to aviation fuel and operational stressors can alter the physical and chemical properties of these fillers. Despite their critical role, there is limited systematic research into how prolonged fuel contact affects the structure and performance of PU foam fillers over time.

Recent technical inspections and statistical analyses have indicated a notable increase in gas turbine engine (GTE) failures, with fuel system components accounting for a significant portion of early engine decommissionings [7]. Investigations during aircraft overhauls have suggested that contamination originating from degraded PU foam fillers may be a contributing factor. It was assumed that detached filler fragments may enter the fuel system, potentially leading to injector clogging, combustion instability, and ultimately, engine malfunction or failure [7].

Disassembly of Su-27 aircraft and analysis of decommissioned components revealed visual and structural deterioration of the tank fillers. These observations support the hypothesis that aging PU foam fillers, through chemical degradation and mechanical breakdown, may contribute to the contamination of aviation fuel and impair the reliability of fuel supply systems. This underscores the urgent need to understand the mechanisms of long-term filler degradation and their implications for fuel system performance and engine reliability.

It is known that most of the military aircraft, including those produced in former USSR like Su-24, Su-25, Su-27, and Mi-8MT helicopters and some Mi-6 modifications, use polyurethane foam fillers in their fuel tanks, which perform several functions [8, 9]. When the tank is partially empty, aviation fuel overflows during maneuvers, which can theoretically lead to the accumulation of static electricity and the appearance of a spark in the tank. A spark can lead to fuel detonation and the destruction of the aircraft. For this reason, the cells of the aircraft tank are filled with foam, which delays the intensive overflow of fuel. The filler is guaranteed to prevent the formation and accumulation of static electricity. The foam prevents the spread of fire in the tank of a military aircraft in the event of an air defense strike. In addition, due to the presence of foam in the tanks, no vibration of the aircraft elements could occur due to fuel fluctuations. Hence, the tank filler also acts as a dampener for fuel fluctuations (judging by the structure, if the material has elasticity) during aircraft evolutions [8].

Backfill and channel fillers are widely used for the explosion protection of aircraft fuel tanks. Today, backfill fillers are practically not used in aviation due to the likelihood of disrupting the order of pumping and supplying fuel to the aircraft engine due to the ingress of spherical elements into the fuel systems. Channel tank fillers made of elastic, highly porous, open-cell polymeric materials such as polyester, polyether, and polyurethane (PU) foam are used to prevent the explosion in aircraft fuel tanks. Full or partial filling of fuel tanks with porous material prevents the explosion of the fuel-air mixture but does not exclude the occurrence of a fire in the space above the fuel level.

Within NATO countries, quality and performance characteristics of fuel tank fillers are defined by the specifications MIL-DTL-83054C [9] and MIL-PRF-87260B [10]. The specification MIL-DTL-83054C was intended for systems not exposed to high static discharge risks and identified five types of foams with specific pore sizes and densities, along with relevant color-coding. Since 2011, it has been valid for products in use and has become inactive for new product designs. The specification MIL-PRF-87260B functionally replaces the previous one in many programs. It covers properties of conductive inerting foam with more stringent requirements to static mitigation. Within this specification, only two grades of foam are identified with no color coding.

Another approach to requirements for foam fillers used in military aircraft is applied to those produced in the former USSR. They are determined by classified Technical Specifications (TU) for a certain aircraft. They do not refer to the MIL specification mentioned above, but in terms of composition, shape, and purpose, these foam fillers are equivalent or compatible with it. General requirements to construction and systems of military aircraft are determined by document [11], which also specify means of fire and explosion protection of fuel tanks.

According to the provisions of [11], the fighters currently used in Ukraine are equipped with reticulated PU foam fuel tank fillers of grade PPU-EO-100 [12]. Disassembly and inspection of fuel system components of military aircraft during their overhaul have revealed a significant level of deterioration of the tank fillers, manifested in changes in color, material brittleness, and other characteristics. This allows to assume that the PU material may have a negative impact on the cleanness and properties of fuel during its use. However, the analysis of the literature has shown that there were no systematic studies on the tank fillers' behavior during long-term use and its possible impact on the operation of the aircraft fuel system and GTE.

The chemical and mechanical reliability of fuel systems and GTE largely depends on the cleanness of the fuels in the aircraft tanks. It is well-known that contaminants in the fuel can harm the operation of aircraft fuel system components, leading to malfunctions in the automatic control of refueling and the required fuel supply, as well as premature clogging of filters [13-15].

The contamination of fuels can be caused by both the technological processes of their production and the processes of transportation, storage, aircraft use, etc.: contaminants can be formed due to wear and tear of friction pairs of units, contact with the environment, or due to physical and chemical changes and the appearance of fuel aging products. Corrosion products from storage, transportation, pumping, and refueling equipment are active catalysts for oxidative processes in fuel, leading to contamination and the formation of deposits. At the same time, oxidation of fuel hydrocarbons and other organic compounds can lead to the formation of amorphous contaminants [16].

It is supposed that PU foam tank fillers can delaminate during long-term operation in an aviation fuel environment due to the oxidation of sulfur, nitrogen, and oxygen compounds inherent in aviation fuels. The amount of such contamination may increase due to the progression of oxidative processes under conditions of elevated temperatures and prolonged contact of fuel with atmospheric oxygen. Thus, it can be assumed that the products of polymer filler degradation not only contaminate the fuel with their residues but are also capable of deteriorating its quality. Therefore, the operational properties of tank fillers, particularly the strength of the morphological structure and the absorption capacity of the material itself, directly affect the chemical and mechanical reliability of aircraft fuel systems and power units. The tank filler may be considered as one of the elements that could lead to deterioration in the chemical and mechanical reliability of fuel systems. Accordingly, this issue required further experimental research.

The operational properties of a polymeric filler are primarily determined by the gas phase content and the cells' morphological structure (material, shape, size, spatial structure) [17-19].

The effectiveness of fuel tank explosion protection depends on the degree of filling the fuel space with porous material. Exposure to high temperatures over a specific period leads to a loss of stability of the porous filler shape and a decrease in its over-fuel volume [17, 19].

As for the analyses of ways to improve the fire resistance of highly porous materials, they are currently being carried out in two directions:

- changing the conditions in which the cell material is located,
- increasing the heat resistance of the cell material.

The relevance of the first direction is due to the high value of the porosity coefficient of the material's cells. For example, the volume of the gas phase in the cells of PU foam reaches 96...97 %. In this case, inert gas or vapors are released into the gas medium from the PU material of the tank filler during heating, which prevents the ignition of gaseous decomposition products of the safety material or reduces the combustion temperature of the medium [20, 21].

The first direction is realized by adding a thermal stabilizer to the PU foam composition. A halogen-containing additive, trichloromethyl phosphate (TCEP), is an example of such a flame retardant [22, 23]. It is widely used today and affects the gas phase. Introducing this or similar additives slows down the ability to ignite and burn.

The second direction is performed due to the priority of the mass of the material of the cells, the ratio of which to the mass of the gas phase is 96.0 % for air and 92.0 % for the fuel-air mixture.

In this case, the heat resistance of the PU material is increased in two ways [21]:

- chemical modification of the material formulation itself,
- introduction of polyfunctional additives into the material.

The introduction of additives in the composition of PU foam is cheaper and can result in the following:

- heat accumulation in the process of phase transitions of type II in refractory material (thermal end effects),
- formation of a film on the surface of the PU material, which protects it from thermal effects and prevents oxygen from entering the material,
- formation of additional compounds in the material.

Regulatory document [12] establishes that PU foam retains operational properties when exposed to aviation fuel TS-1 and RT for 8 years. At the same time, we assumed that the change in the morphological structure of the material of PU foam begins earlier than the established period. Additionally, it is noted that PU tank fillers are not typically replaced, as the regulatory document allows for the use of PU foam for up to 8 years.

Therefore, it can be assumed that the operational reliability and thermal stability of the polymeric channel fillers of tanks operated in the environment of aviation fuel change over time due to the influence of the aging process [24]. Such prolonged use leads to a change in the morphological structure of the polyurethane foam filler, which subsequently results in its destruction, crumbling, and contamination of the aviation fuel.

Timely cleaning of fuel system fluids increases the reliability and durability of equipment. When operating on contaminated fuel, precision pairs in the fuel injection pumps may jam, causing engine start instability, speed fluctuations, or shutdown. Studies have shown that only by cleaning and improving the purity of the working fluid can the durability of the fuel system and equipment increase by 2–3 times [13-15]. Therefore, the issue of improving fuel purity for GTEs is also particularly relevant.

The identified problem has necessitated experimental studies aimed at investigating the impact of aging on the thermal stability and operational reliability of the PU foam tank fillers and developing measures to minimize it. The primary aim of this study is to evaluate the effects of long-term aging on the structural integrity, thermal stability, and operational reliability of PU foam fillers used in military aircraft fuel tanks. Specifically, the study aims to investigate how prolonged exposure to aviation fuel and thermal cycling affects the morphological and functional characteristics of PU fillers, potentially compromising fuel system performance and aircraft safety. To achieve this aim, the following tasks should be solved:

- determining the impact of aging on the thermal stability of polyurethane foam fillers by analyzing changes in their morphological properties after prolonged exposure to aviation fuel,
- establishing the optimal service life for PU foam fillers by identifying the period over which their structural and functional properties begin to degrade significantly during use in fuel tank environments,
- conducting thermogravimetric and microscopic analyses to evaluate the degradation patterns and structural changes in PU foam fillers at various aging stages,
- analyzing the possible influence of aged PU foam fillers on the operational reliability of aircraft fuel systems, particularly their role in fuel contamination and system malfunction risks,
- developing recommendations for enhancing the long-term performance and stability of PU foam fillers by proposing material modifications, operational guidelines, or replacement intervals.

2 Materials and Methods

In the framework of this work, the degradation of PU foam of grade PPU-EO-100 under the influence of high temperatures and long-term storage in the aviation fuel environment was investigated.

During this experiment, the PU foam of grade PPU-EO-100 "Regicell 20" (Germany), which meets the requirements of [12] and is used as a PU filler for the fuel tanks, was studied. PU foam filler contains TCEP, which is a fire-retardant substance. Three samples of PU foam material of size $50 \times 25 \times 15$ mm, with different periods of use, were investigated (Fig. 1). Sample 1 was cut from a new foam filler that was not installed in the fuel tank and was not exposed to aviation fuel. Samples 2 and 3 were cut from foam filler extracted from the fuel tanks of Su-27 fighters during overhaul. The PU fillers from which samples 2 and 3 were taken were installed in fuel tanks and were exposed to aviation fuel for 5 and 10 years, respectively. Basic physical properties of the new PU foam provided by the supplier are given in Tab. 1.

a *b* *c*

Fig. 1 General view of the tested samples:
a – sample 1 was not installed in the fuel tanks;
b – sample 2 was installed in the fuel tanks and exposed to aviation fuel for 5 years*;*
c – sample 3 was installed in the fuel tanks and exposed to aviation fuel for 10 years

One of the primary and most dangerous sources of high-temperature exposure to polymeric fuel tank fillers is combustion due to fire damage. To determine the behavior of the material of the polymeric channel filler in the conditions of an advanced fire in the aircraft fuel tank, the heat resistance of polymeric channel filler samples was studied at temperatures corresponding to the combustion of the fuel-air mixture in a closed volume.

Tab. 1 Physical properties of new PU foam tank filler of grade PPU-EO-100

Property	Unit of measurement	Value
Color	–	white
Density	kg/m^3	30.0
Compression load deflection	kPa, 25 %	3.3
	kPa, 65 %	6.1
Tensile strength	kPa	122.0
Elongation at break	%	229.0
Compression set by 50 % at 70 °C during 22 hours	%	10.0
Cell size	mm	3.2
Pollution by firm particles	mg/m^3	230.0
Fuel retention	%	2.1
Fuel displacement	%	2.7

Samples of polymeric filler for the fuel tanks were tested using the derivatography method [25]. The advantage of using complex derivatography is that the simultaneous determination of transformations in a substance with a thermal effect and changes in its mass allows the unambiguous establishment of the nature of the processes, which is very difficult to do based on the results of the thermal method only. For example, this is useful when phase transformations accompanied by the thermal effect occur without a change in mass.

A derivatograph typically records thermal and thermogravimetric changes in substances, including polymers and rubber compound ingredients [24]. Modern derivatographs enable synchronous analysis using multiple methods, including differential thermal analysis (DTA), thermogravimetric analysis (TGA), and differential thermogravimetry (DTG). In particular, they allow recording simultaneously four dependencies: temperature difference ΔT of the sample to be analyzed and the reference over time (DTA curve); mass change Δm with temperature (thermogravimetric curve TGA); rate of mass change (derivatives dm/dt) with temperature (differential thermogravimetric curve DTG) and temperature (curve T). Such an approach enables the establishment of the sequence of substance transformations and the determination of the amount and composition of intermediate products.

This study utilized a laboratory complex equipped with means for measuring test parameters, transmission, registration, and processing of the obtained data to investigate the nature of thermal destruction of the polymeric channel filler in fuel tanks.

The PU foam material samples, 4 mg each, were analyzed by Linseis STA PT1600 derivatograph (Germany) with heating in an air atmosphere at 100 °C/min, up to 1 000 °C. The accuracy of temperature measurement is ± 1 °C. A sample of α-Al_2O_3 was used as a reference for comparison. Three dependencies were recorded during the measurement process, namely, changes in the sample mass with increasing temperature (thermogravimetric curve – TGA), changes in the thermal effects of the sample (high-temperature differential scanning calorimetry curve – HDSC), and changes in temperature over time. Next, the change rate in the sample's mass was calculated (differential thermogravimetric curve – DTG).

The degree of degradation of the polymeric filler of fuel tanks during long-term operation was determined by changes in its morphological structure due to constant contact with hydrocarbon aviation fuel. An optical microscope, "Celestron microscope digital imager" (Celestron LLC, USA), was used to examine the structure of PU foam filler samples. Observation of samples was done under × 150 magnification. Images of the morphological structure of samples were taken using a digital camera installed in the microscope.

3 Results and Discussion

3.1 Investigation of the Heat Resistance of the Samples of the Polymeric Channel Tank Filter

The results of studies of changes in the thermophysical properties of fuel tank filler samples under the influence of high temperatures are shown in Figs 2–4.

A detailed analysis of the thermogram (Fig. 2) of a sample of a new polymeric filler that was not installed in fuel tanks (Sample 1) shows that the change in the thermophysical properties of the material begins to be observed at a temperature of 227 °C (HDSC curve). A significant and intensive decrease in the weight of the sample of 75 % was observed in the temperature range of 212–430 °C (TGA and DTG curves). With a further increase in temperature, the sample completely burns; complete burning occurs within the temperature range of 460–928 °C (TGA curve). The study recorded that during the heating of the sample, a heat release of 4.3272 J/kg was observed.

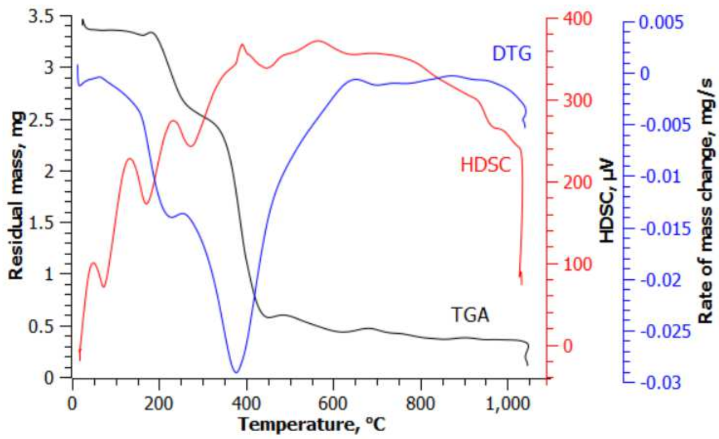


Fig. 2 Thermogram of the PU foam filler sample, which was not installed in fuel tanks

The thermogram (Fig. 3) of the polymeric filler, which was exposed to aviation fuel for 5 years (Sample 2), shows that the change in thermophysical properties began at a temperature of 205 °C (HDSC curve), which is comparatively lower than for the sample of new filler. The sample lost weight within a narrower range of temperatures, 235–355 °C (TGA and DTG curves). The weight was decreased by 17 % within this temperature interval, and the complete burning of the sample was observed in a 355-922 °C interval (TGA curve), significantly wider than for the new polymeric filler. The amount of heat released and recorded in the sample heating was 13.8424 J/kg.

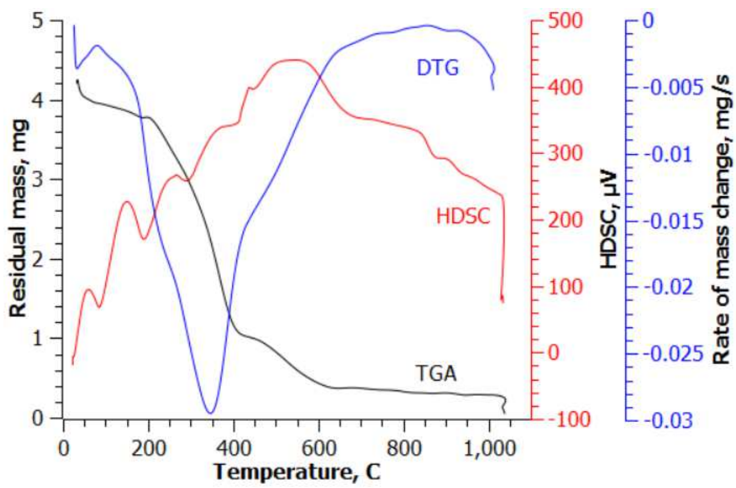


Fig. 3 Thermogram of the PU foam filler sample, which was exposed to aviation fuel for 5 years

A detailed analysis of the thermogram (Fig. 4) of a sample of the polymeric filler, which was exposed to aviation fuel for 10 years (Sample 3), shows that the change in thermophysical properties began to be observed at a temperature of 201 °C (HDSC curve). Reduction of sample weight was observed in the temperature range of 230–

390 °C (TGA and DTG curves); within this interval, the sample weight was reduced by 19 %. Complete burning of the sample is observed during further heating in a temperature interval of 390–830 °C (TGA curve). The heating process was accompanied by the release of heat in an amount of 13.8424 J/kg, which is quite similar to that of Sample 2.

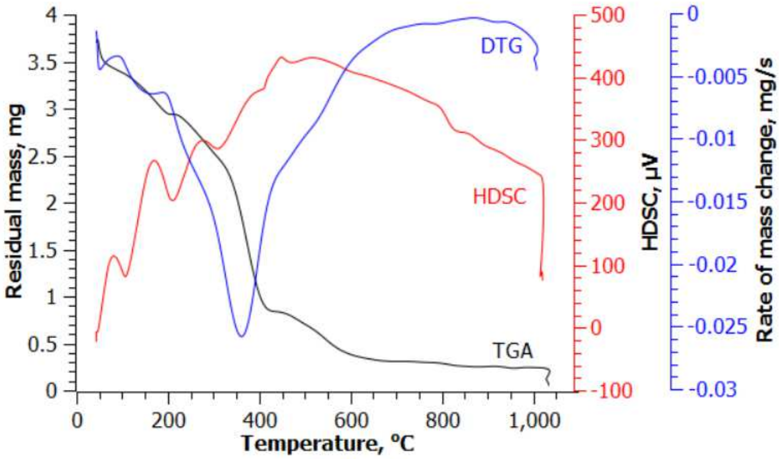


Fig. 4 Thermogram of the PU foam filler sample, which was exposed to aviation fuel for 10 years

Analysis of experimental data obtained through derivatography of the PU foam fillers with varying exploitation periods enabled the following conclusions to be drawn.

The ignition temperature of the PU foam filler with TCEP during material aging shifts to the region of lower temperatures, which can be seen in the HDSC curves. This is due to the gradual destruction of its structure and, as a result, the disruption of internal connections in the material. In addition, with a decrease in the concentration of the fire-retardant additive in the composition of PU foam, the adsorption capacity of the material increases due to the constant presence in the environment of aviation fuel, which in turn also contributes to a decrease in the ignition temperature of polyurethane foam.

At the same time, the results of measuring the amount of heat released during the combustion of PU samples indicate that their ability to absorb heat during aging decreases by about three times. This effect is also attributed to material degradation and a decrease in the content of the flame-retardant additive. These results also confirm the beneficial effect of the flame-retardant additive on the material’s gas phase.

The analysis of the DTG and TGA curves on the thermograms has shown that for PU foam samples, which were exposed to fuel for 5 and 10 years, the material's heat resistance decreased compared to the sample of new PU foam. Thus, for Sample 2 compared to Sample 1, the temperature at which the sample mass began to decrease significantly dropped from 430 °C to 355 °C, and for Sample 3, it decreased to 390 °C. The analysis of the TGA curves of the thermograms shows that with the aging of the PU material, the temperature at which the sample completely burns down also significantly decreases.

Thus, from the HDSC curves in the thermograms, it can be seen that in the area of up to 400 °C, the decomposition process of the samples is accelerated and shifted to higher temperatures.

Thus, the analysis of the experimental data showed that the aging process of PU foam material reduces its heat resistance. This is primarily due to a change in its morphological properties and a decrease in the content of the fire-retardant additives during operation in the aviation fuel environment.

3.2 Investigation of Polymeric Channel Tank Filler Degradation During Long-Term Operation

Next, the degree of degradation of the polymeric filler of fuel tanks during long-term operation was determined by changes in its morphological structure due to constant contact with hydrocarbon aviation fuel.

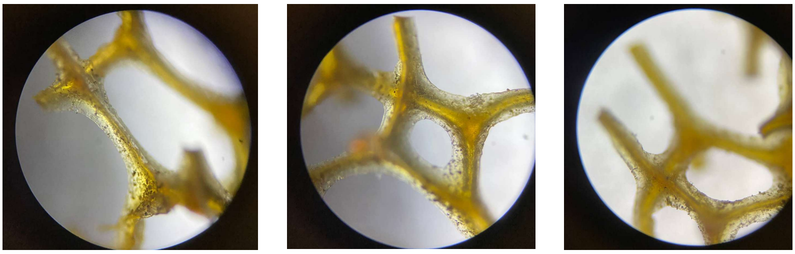
Sample 1 of a new PU foam filler, which was not installed in fuel tanks (Fig. 5), looks like a pure white sample, clearly showing a structure similar to that of a sponge. This structure consists of individual cells of various shapes, including hexagons, and these cells are arranged in multiple rows. The entire structure is a frame that forms the cells. The cell wall is an element of the frame (dark line) with an uneven layer of transparent coating.

a b c

Fig. 5 Microphotographs of the PU foam filler sample, which was not installed in fuel tanks, magnification × 150

Microphotographs of Sample 2, which was exposed to aviation fuel for 5 years, are shown in Fig. 6. It is seen that the coating has changed its color from white to brown, and the shape and size of the channels have changed. The walls of the cells became yellow, the frame line was not visible, and black dots (particles) appeared, the nature of which is not identified. These could be pores in the wall material or deposits of newly formed particles that may have resulted from the contact with fuel, which is more likely. The number of dark inclusions increases significantly in the film inside the cells. A noticeable reduction in the wall coating material within the cells is observed, along with the emergence of structural irregularities. Additionally, breaks in the cell walls are evident. The ruptures are sudden, as there is no thinning of the walls, typical of gradual destruction. Black inclusions may be foreign microparticles suspended in the fuel and not removed during filtration. They can be deposited on the cell walls due to contact with the fuel. Compared to the others, the lighter inclusions are fragments of the coating with a double frame line, with broken walls and dark dots. A chaotic arrangement of the destroyed walls was found. An increase in the concentration of black particles is observed, especially on the overlay coating inside the cells.

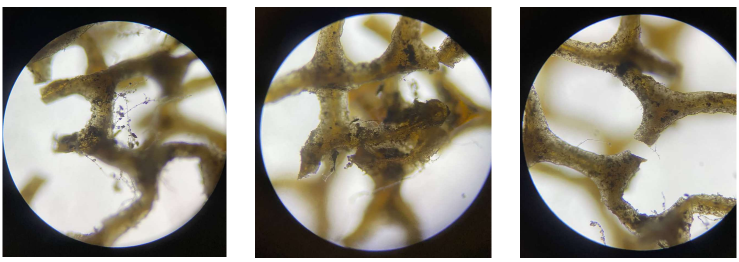
A characteristic feature of all the destroyed walls is a significant decrease in the coating overlaps inside the cells.



a b c

Fig. 6 Microphotographs of the PU foam filler sample, which was exposed to aviation fuel for 5 years*, magnification* × 150

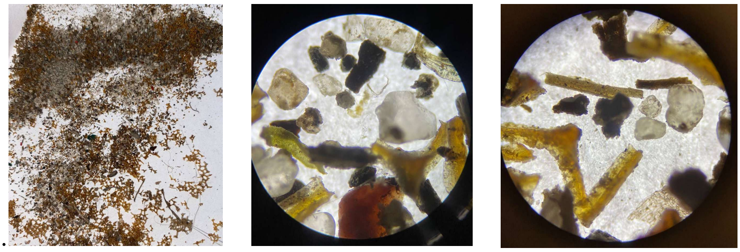
Microphotographs of Sample 3, which was exposed to aviation fuel for 10 years, are shown in Fig. 7. There is a noticeable color change compared to the sample of the new filler and the sample that has been in operation for five years. The investigated sample (Figs 7a and 7b) has a dark gray-brown color, and there are changes in the size and shape of the cells. The microphotographs clearly show the destroyed cell walls. Particles contained freely in the fuel settle on the walls and form entire concentration zones. The overgrowth of the coating material, which partially occupied the space of the cells, has almost disappeared. Distortion of the cell shape was observed. Black particles are deposited on the wall and chaotically located concentration zones are visible. Such zones can appear in shaded areas where the fuel flow rate is lower than in the main flow, and the fuel does not wash away the particles. In one of the cells, threads appeared that crossed the space of the cell and held particles of different sizes (Fig. 7a). The destroyed cells are heavily contaminated with black particles; in the central cell in the figure, almost the entire internal space is filled with various deposits. It is visible how the shape of the cells is distorted due to the aging of the material or external forces. The material's color has changed significantly, making the elements of the wall frame barely visible.



a b c

Fig. 7 Microphotographs of the PU foam filler sample, which was exposed to aviation fuel for 10 years*, magnification* × 150

Finally, the pollution on the surface of the filler cells was investigated (Fig. 8). Microphotographs of the surface of the PU foam channels and the channel space between the channels showed that its surface is contaminated with debris of various origins (chemical analysis of the debris was not performed); most likely, these are blown out corrosion of fuel tanks and other rubber parts inclusions (Fig. 8a). Black inclusions (Figs 8b, c) may be foreign microparticles present in the fuel in suspension and not removed during filtration. They can be deposited on the cell walls when the cell is in contact with the fuel. Lighter particles are likely to be fragments of the coating with a double frame line, with broken walls and dark spots. The coating material does not withstand long-term operation, as it is destroyed by natural aging or applied loads, which compromise the coating structure.



a b c

Fig. 8 Microphotographs of the pollution on the surface of the canals:
a – magnification × 20*, b, c – magnification* × 150

These results suggest that the microparticles of contaminants identified during the study may enter the aircraft fuel system and can be carried by the fuel flow into the combustion chamber during operation. Later, these contaminants can be deposited in the fuel injector elements, impairing performance.

4 Results and Discussion

During the experimental studies, the influence of the aging process on the thermal stability of the polymeric channel filler of the military aircraft fuel tanks was confirmed by the identified changes in its morphological structure and properties when operating in the aviation fuel environment.

It can be assumed that to preserve the morphological properties of the PU foam material and obtain the desired dependence of its mass loss on temperature during its aging, it is necessary to:

- to replace PPU-EO-100 units promptly, determine the optimal service life of the polymeric channel filler in the aviation fuel environment, considering the material's aging,
- to modify the thermophysical properties of the tank filler material at the manufacturing stage by adding polyfunctional flame retardants that act mainly on the material itself,
- to modify the structure of the cell elements of the polymeric channel filler for tanks.

Microscopic analysis of the filler structure enabled the establishment that the samples presented show a good indication of the impact of the facility's service life on the technical condition of the fuel tank coating. Based on the results of the analysis of the foam filler samples, the following conclusions and assumptions can be drawn.

The coating material and the PU foam filler itself do not withstand long-term operation, which destroys the coating structure due to its natural aging or applied loads.

During fuel use, suspended microparticles of the PU foam filler and its coating, formed as a result of long-term operation, enter the fuel tank. These microparticles can be carried by the fuel volume and cause accelerated clogging of the aircraft fuel system filters.

This allows us to make a further assumption that the fuel flow carries fine particles of destroyed fragments of the PU foam filler, which are not retained by fuel filters, further into the combustion chamber. These particles can settle on the fuel injector elements, causing coking of the nozzles and reducing their efficiency. Although the presence of particulate contaminants originating from degraded PU foam filler was confirmed microscopically, a comparative analysis of these particles' size and chemical composition against those found in clogged fuel nozzles, as reported in [7], was not conducted. Such analysis presents a prospect for additional research during future studies to conclusively establish the causal pathway between filler degradation and nozzle coking.

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List of abbreviations

DTA – differential thermal analysis
DTG – differential thermogravimetry
GTE – gas turbine engine
HDSC – high-temperature differential scanning calorimetry
PU – polyurethane
TCEP – trichloromethyl phosphate
TGA – thermogravimetric analysis

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