



Blocking of Fuel Filter in Aircraft by an Accelerator Blooming

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가류 촉진제 블루밍에 의한 전투기 연료필터의 막힘

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ABSTRACT : Blocking of fuel filter in aircraft greatly can affect loss of pilot's life and of the aircraft. The investigation of failures is, thus, of vital importance in preventing incidents in advance. The fuel filter of aircraft plays an important role in filtering various debris from jet fuel. It filters impurities smaller than 10 μm particles from jet fuel provided with the speed of 1,330 pounds per hour. It must be replaced per 500 h on the basis of operating time. However, even before reaching 500 h, the warning sign lighted on due to blocking of fuel filter. Recently, these similar defects have happened repeatedly. Therefore, in this study, the cause of blocking fuel filter in aircraft was investigated using various analytical techniques such as FT-IR microscopy, FE-SEM/EDS, and total sulfur determinator. Consequently, the blocking material of fuel filter was identified to an accelerator from the integral fuel tank sealant. And a mechanism for the formation of the blocking material of fuel filter by an accelerator blooming phenomenon in fuel tank was suggested.

요약 : 전투기 연료필터의 막힘은 조종사 생명과 전투기의 손실에 큰 영향을 줄 수 있다. 따라서 결함 연구는 사고를 미연에 방지하는데 매우 중요하다. 전투기 연료필터는 제트 연료에 포함된 다양한 불순물을 여과하는 중요한 기능을 수행한다. 연료 필터는 시간당 1,330 파운드의 유속으로 공급되는 제트 연료에 함유된 10 μm 크기 이하의 불순물을 여과한다. 필터는 운영시간 기준 500 시간마다 교체되어야 한다. 그러나 500 시간이 도달하기 훨씬 전에 연료 필터의 막힘 현상으로 경고등이 켜지고 있다. 이와 같은 유사한 결함이 최근에 반복적으로 발생하고 있다. 그러므로, 이 연구에서는 전투기의 연료 필터 막힘에 대한 원인을 FT-IR microscopy, FE-SEM/EDS, 총 황함량 분석기와 같은 다양한 분석기술을 이용하여 조사하였다. 결론적으로, 연료 필터를 막히게 한 물질은 내부 연료 탱크용 실란트에서 기인한 가류 촉진제로 확인되었다. 그리고 연료 탱크내에서 가류 촉진제 블루밍 현상에 의해 연료필터를 막히게 하는 물질의 형성에 대한 메커니즘을 제시하였다.

Keywords : fuel filter, aircraft, blocking, accelerator, blooming, sealant

I. Introduction

Like most of commercial airplanes, aircraft carry their fuels in integral fuel tanks.¹ An integral fuel tank is the primary aircraft structure as integral part of wing or fuselage, that is sealed to contain fuel, in contrast to a rubberized fuel cell mounted in aircraft structure. Integral fuel tanks are most efficient way to carry fuel and nearly all modern aircraft utilize this type of fuel tank. During manufacturing, great care is taken to protect the fuel tanks against future corrosion and the possibility of fuel leaks. Before assembly is begun, the aluminum

parts which will make up the integral fuel tanks are anodized with sulfuric acid to reduce their susceptibility to corrosive attack. In sulfuric acid anodizing, a thin layer of inert oxides as alumina (Al_2O_3) is caused to form on exposed metal surfaces. This inhibits further chemical action and helps protect the base material from a variety of corrosive influences. As the further protection, a corrosion preventive coating is applied to all detail parts after anodizing process is complete. The second coat containing a biocidal additive is applied to the parts immediately after applying the first coat. The corrosion preventive coating is then cured at about 100°C for 1 h. The next manufacturing steps are directed to toward ensuring that the tanks are thoroughly sealed against fuel leakage. After the

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corrosion preventive coating has cured, a leakage preventive coating is applied to joints and rivets to prevent fuel leaks. Although there are many kinds of tank sealants, the tank sealant that is commonly used in aircraft is a polysulfide sealant designed to meet Aerospace Material Specification (AMS-8802C).² It adheres well to bared or anodized aluminum, titanium, steel, and other materials. It is generally resistant to most fuels and oils used in aviation. After all manufacturing processes, fuel tank is cleaned, dried, and filled up JP-4 fuel.

Figure 1 shows a schematic cross-section of fuel pump.³ JP-4 fuel from the fuel tank enters the fuel pump chamber through a 74 μm (200 mesh) inlet screen via oil-to-fuel heater. Two pump gears increase the fuel pressure and deliver to the fuel control unit (FCU) via a 10 μm fuel filter in the pump outlet. In case that the fuel filter become blocked, a bypass valve in the pump body enables unfiltered high pressure fuel to flow to the FCU.

Because a 10 μm fuel filter was blocked by an unknown material, the warning sign at display of the front panel lighted on. Recently, a lot of similar defects that fuel filter is blocked have often occurred in aircraft while flying.

In this study, the cause of blocking fuel filter in aircraft was investigated. The blocking material of fuel filter was identified and a mechanism for the formation of the blocking material by an accelerator blooming in fuel tank was also suggested.

The analytical techniques were used with Fourier transform-infrared (FT-IR) microscopy, field emission scanning electron microscopy/energy dispersive X-ray spectroscopy (FE-SEM/EDS), and total sulfur determinator.

II. Experimental

Two failed fuel filters [(a) and (b)] and the unfailed fuel filter (c) are shown in Figure 2. Two failed fuel filters are blocked by an unknown material even before than criteria of exchange period. The failed fuel filter (a) is much more severe than the failed fuel filter (b), meaning further contamination of filter. The more severely failed fuel filter (a) is somewhat denser brownish color than the less severely fuel filter (b). The unfailed filter (c) is introduced to compare with two failed filters in the same conditions.

Before disassembling fuel filter, extraction of impurities existing in the outside of two failed fuel filters with an ultrasonicator in *n*-hexane is performed for 10 min. The extraction solution is separated into a yellow-brownish liquid and blackish particles by filter paper (No. 10). After completely evaporating solvent from separated solution by heating, the component of oily liquid remaining is identified with FT-IR microscopy (Smiths, IlluminatIR-II, USA). FT-IR spectra are taken on thin film. The liquid samples are scanned from 400~4000

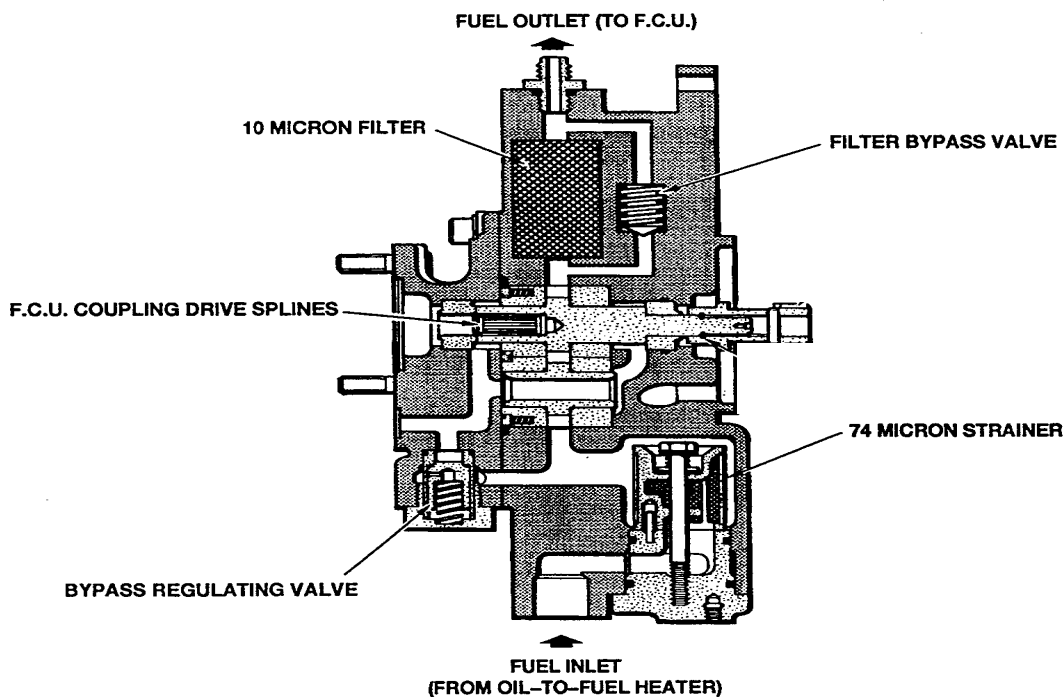


Figure 1. A schematic cross-section of fuel pump.

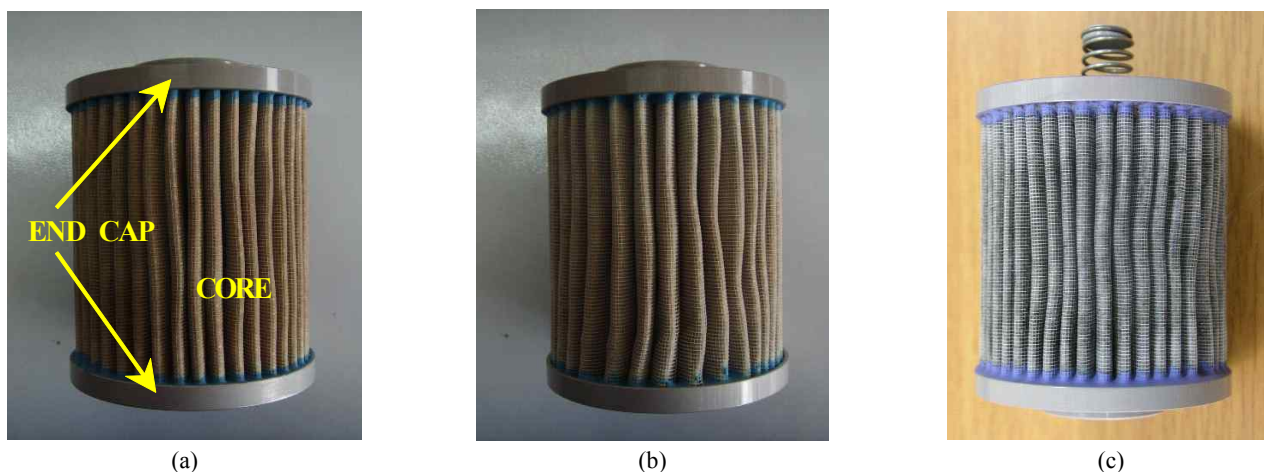


Figure 2. Fuel filters (a) in the more severely failed, (b) in the less severely failed, and (c) in the unfailed.

cm^{-1} with a resolution 4 cm^{-1} and the average of 32 scans for samples is taken for the measurement. The morphology of particles is observed by FE-SEM (Hitachi, S-4700, Japan) at an accelerating voltage of 20 kV. Chemical elements of blackish particles are analyzed by EDS (Horiba, EMAX, Japan) at an accelerating voltage of 15 kV. Blackish particles are washed three times with *n*-hexane and solvent is eliminated thoroughly at 80°C oven for 1 h.

In order to analyze impurities from inside of fuel filter, two failed fuel filters are disassembled. It is composed of two parts, two end caps and its core as indicated in Figure 2(a). Two end caps help in supporting fuel filter on both sides. Its core of fuel filter has five layers which are made up of fiber filter, protecting layer, main filter, protecting layer, and steel filter in order of fuel flow from outer to inner. The main filter among five layers plays a significant role in filtering impurities from fuel. The morphology of particles is observed by FE-SEM at an accelerating voltage of 20 kV. Chemical elements of dark brownish particles on main filter are also identified with EDS at an accelerating voltage of 15 kV. The main filter is washed three times with *n*-hexane and solvent is eliminated thoroughly at 80°C oven for 1 h.

In order to know the influx pathway of sulfur, the reaction of the blocking material with copper wire in acid-buffer solution is performed. Sulfur particles on main filter are dissolved in acid-buffer solution (pH 4.0) and copper wire is added. Reduced or oxidized state of sulfur is determined by color change on copper surface due to formation of copper sulfide (CuS).

In order to identify what source of the influx pathway for the blocking material of fuel filter, two materials such as JP-4 fuel and an integral fuel tank sealant are investigated. Sulfur content of JP-4 fuel is measured by total sulfur determinator (LECO Co., SC-632, USA). About 0.10 g of sample is measured three times and averaged. A sealant (WS-8020 RC Class

A 1/2) is supplied by Flamemaster corporation in USA and composed of two parts in liquid paste form, Part A and Part B. Compositions of Part A and Part B in sealant compound based on material safety data sheet offered from the manufacturer are given in Table 1. Sulfur in Part A is identified and quantified with EDS at an accelerating voltage of 15 kV.

Prior to use, the sealant must be mixed in the proportion of 100 parts of Part B to 10 parts of Part A by weight based on specification. It was doubted that sulfur blooming resulted from excessive loading of part A (including an accelerator) or Part B (including polysulfide polymer) during manufacturing. To know the effects of sulfur blooming on the mixing ratios of Part B/Part A of sealant, three sealant compounds are prepared by mixing ratios of 100/10, 100/20, and 100/40 in Part B/Part A, respectively. Before weighing, each part should be stirred separately. Part B (white) is then added to Part A (black) and mixed thoroughly until a uniform grey color is reached. There should be no white or black streaks in the mixture. Each

Table 1. Compositions of Part A and Part B in Sealant Compound Based on Material Safety Data Sheet Offered from the Manufacturer

Sealants	Compositions	wt%
Part A ^{a)}	MnO ₂	30.0~60.0
	Carbon black	1.0~5.0
	Butyl benzyl phthalate	40.0~50.0
	An accelerator ^{b)}	1.0~5.0
Part B	Polysulfide polymer ^{c)}	50.0~70.0
	TiO ₂	1.0~5.0
	CaCO ₃	1.0~5.0
	Toluene	1.0~5.0
	Ethyl acetate	10.0~20.0

^{a)} Including about 3.0 wt% sulfur identified with EDS.

^{b)} Classified as trade secret of the manufacturer.

^{c)} Including the terminal thiol end groups (-SH) on both sides in a polymer.







Sample I.D.	Extracts after ultrasonication in <i>n</i> -hexane	After separating by filter paper	
		Liquid	Blackish particles
(a)			
(b)			

Figure 3. Extraction of impurities from outside of fuel filter (a) in the more severely failed, (b) in the less severely failed.

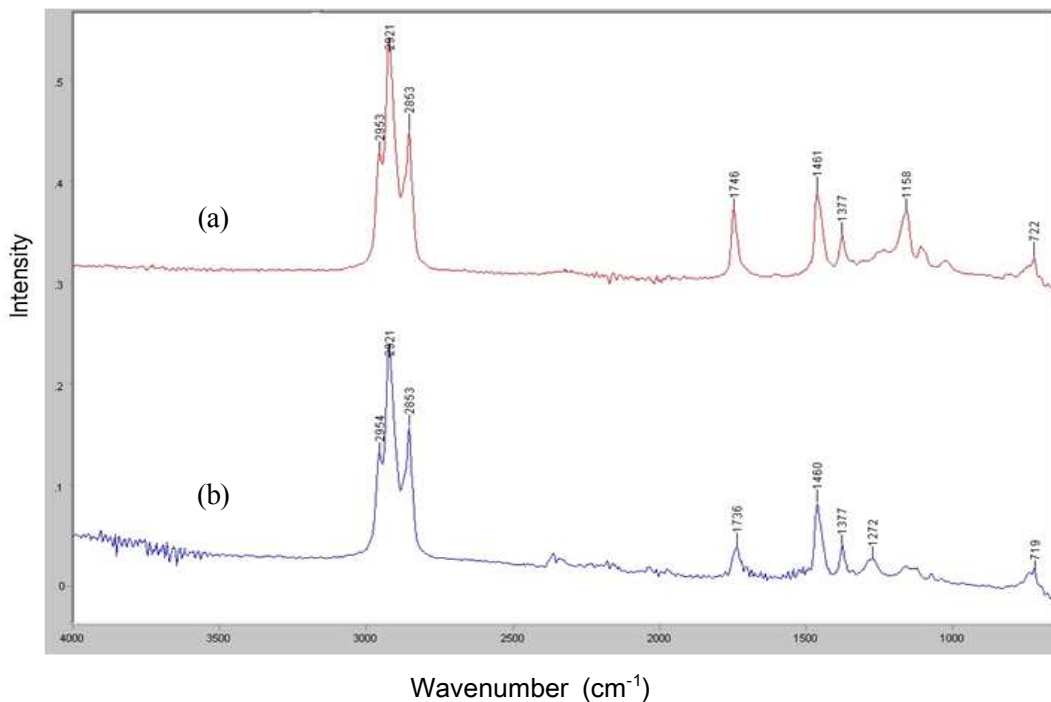


Figure 4. FT-IR spectra of yellow-brownish liquid for (a) the more severely failed fuel filter and (b) the less severely failed fuel filter.

compound is cured at room temperature for 3 days. An accelerating experiment is performed at 125°C oven for 3 days. The relative sulfur content is measured by EDS. An EDS system is used in the characterization of materials through the use of ionizing radiation to excite a sample. This excitation generates

X-ray energies that identify the elemental composition of the sample. Using X-ray detection equipment to count the number of X-ray photons emitted by this technique, an EDS system is able to characterize and quantify in an approximate manner the elemental compositions of the sample. Semi-quantitative

sulfur analysis is performed in the same conditions such as an accelerating voltage (15 kV), livetime (100 secs), working distance (10 mm), and area (1 mm x 1 mm). Sulfur at both the inner site and the surface for each compound after aging is measured. The relative abundance of migration of sulfur to surface is calculated from the peak height, based on peak height (100) at the inner site after aging.

III. Results and Discussion

1. Extraction of Impurities from Outside of Fuel Filter

Before disassembling the fuel filter, extraction of impurities from outside of two failed fuel filters was performed. After completely digging fuel filter in *n*-hexane, an ultrasonicator was worked about 10 min. Figures 3(a) and (b) show that the extract of the failed fuel filter (a) is more black-brownish than that of the failed fuel filter (b) in beaker. Each extract is separated into a yellow-brownish liquid and blackish particles by filter paper (No.10). A yellow-brownish liquid is evaporated by heating and then identified with FT-IR microscopy. Figures 4(a) and (b) show the IR spectral patterns of yellow-brownish liquid for two failed fuel filters. A yellow-brownish liquid of two failed fuel filters is identified to

Table 2. Characteristic FT-IR Peaks on Yellow-brownish Liquid Extracted from Two Failed Fuel Filters

Components	FT-IR band, cm^{-1}	Chemical structure
An Ester Oil	2953, 2921, 2853	CH_3 (Methyl), $-\text{CH}_2-$ (Methylene)
	1746, 1736	$\text{C}=\text{O}$ (Carbonyl)
	1461	$-\text{CH}_2-$ (Methylene)
	1377	CH_3 (Methyl)
	1158, 1272	$-\text{C}-\text{O}$ Bond
	Near 723	$-\text{CH}_2\text{CH}_2-$ (Dimethylene)

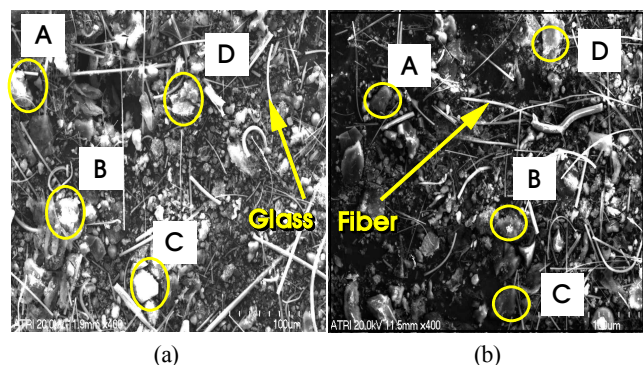


Figure 5. SEM photographs of blackish particles for (a) the more severely failed fuel filter and (b) the less severely failed fuel filter.

an ester oil, showing characteristic peaks at both 1736 cm^{-1} or 1746 cm^{-1} indicating carbonyl group ($-\text{C}=\text{O}$) and 1272 cm^{-1} to 1158 cm^{-1} indicating C-O bond as described in Table 2. An ester oil is generally used as the fluid oil in aircraft. This oil seems to be come in fuel in the middle of fuel flow. Because this oil has a large molecular weight distribution, It maybe seems that this oil can not penetrate the fuel filter. Figures 5(a) and (b) show SEM photographs of blackish particles for both the more severely failed and the less severely failed fuel filter. The SEM photographs (a) and (b) taken in blackish particles show a few particles of about $20 \mu\text{m}$ in size, some fine particles, and some fine long fragments. Some fine long fragments may be made during extraction process by an ultrasonicator.

As shown in Figures 6(a) and (b), chemical elements about blackish particles (A, B, C, and D) indicated in Figure 5(a) and (b) are analyzed with EDS. Chemical components for blackish particles in two failed fuel filters are identified to S, Si, Al, Ca, Mg, and K. The results showed that the peak intensity for chemical elements was the highest in sulfur, meaning the largest amount of all other elements. As represented in Figure 5(a) and (b), long linear fragments are considered as glass fiber. Glass fiber is generally used as material of fuel or oil filter in aircraft. Glass fiber mainly includes chemical elements such as Si, Na, Al, Ca, K, and Mg. It is inferred that the fragments of glass fiber come from main filter during extraction process as the result of ultrasonication. Therefore, as shown in Figure 6(a) and (b), chemical elements such as Si, Al, Ca, Mg, and K except S for all blackish particles are considered as those of glass fibers. All blackish particles from outside of two failed fuel filters are identified to sulfur.

In summary, a yellow-brownish liquid and blackish particles extracted from outside of two failed fuel filters were identified to sulfur and an ester oil, respectively. However, it was considered that both of them do not affect directly on blocking fuel filter because of relatively very small quantity.

2. The Remnants from the Main Filter

As stated previously, the fuel filter was composed of two parts, two end caps and core. Two end caps were supporting fuel filter on both sides. A core of the fuel filter was disassembled. Its core has 5 layers which are comprised of fiber filter, two protecting layers, main filter, and steel filter as given in Figure 7. There was fiber layer at the most outside. Fuel to fuel filter flows from outer layer to inner layer, in order of fiber filter, a protecting layer, main filter, a protecting layer, and finally steel filter. Two protecting layers protect the main filter. The main filter plays a significant role in filtering impurities smaller than $10 \mu\text{m}$ from fuel. Compared with the unfailed main filter, two failed main filters was stained

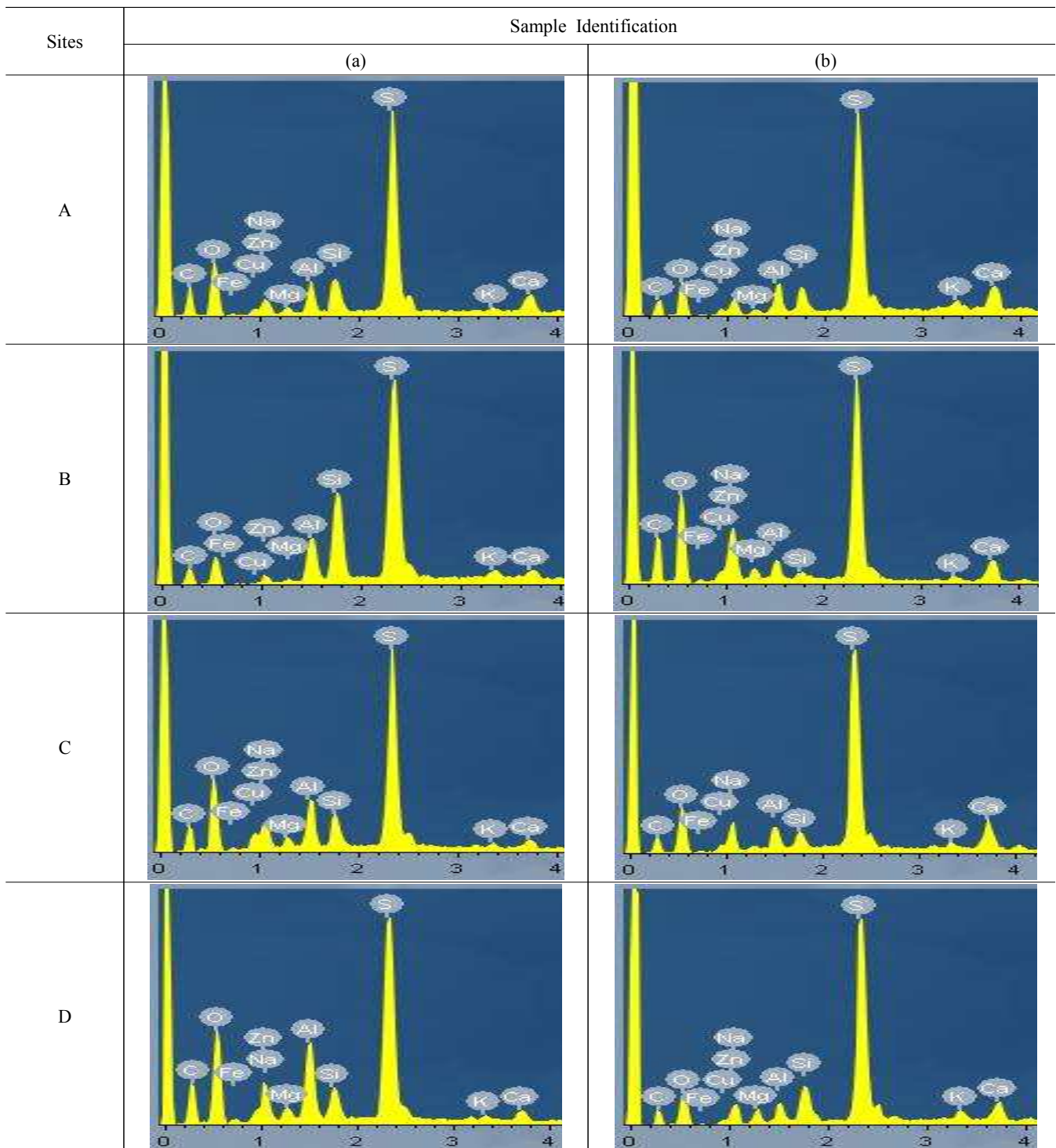


Figure 6. EDS spectra of blackish particles (A, B, C, and D) indicated in Figure 5 in (a) the more severely failed fuel filter and (b) the less severely failed fuel filter.

black brownish. Before analyzing, the main filters were washed off with *n*-hexane and dried thoroughly. Figures 8(a), (b), and (c) show SEM photographs and EDS spectra for the remnants of main filters in the more severely failed, the less se-

verely failed, and the unfailed, respectively. The remnants of photograph (a) show even more fine particles than those of photograph (b), coinciding with the result of earlier blocking of fuel filter. The main filter is completely covered with these

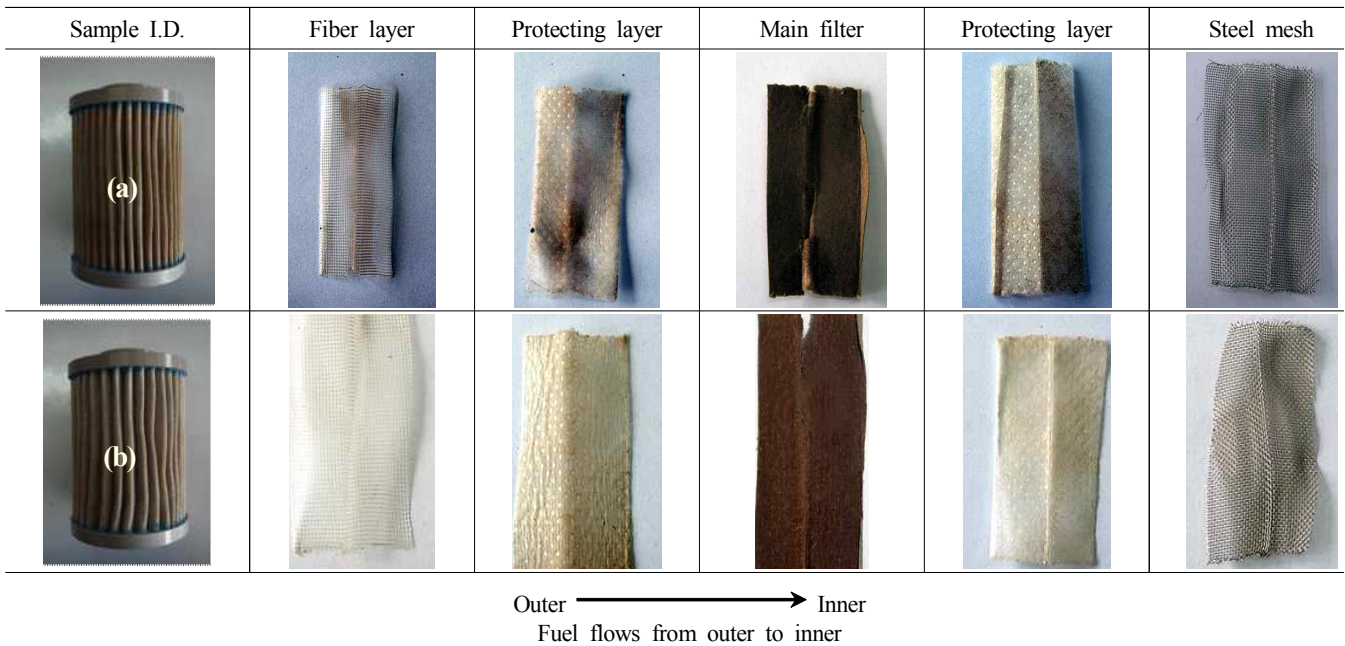


Figure 7. Disassembled fuel filters for (a) the more severely failed and (b) the less severely failed.

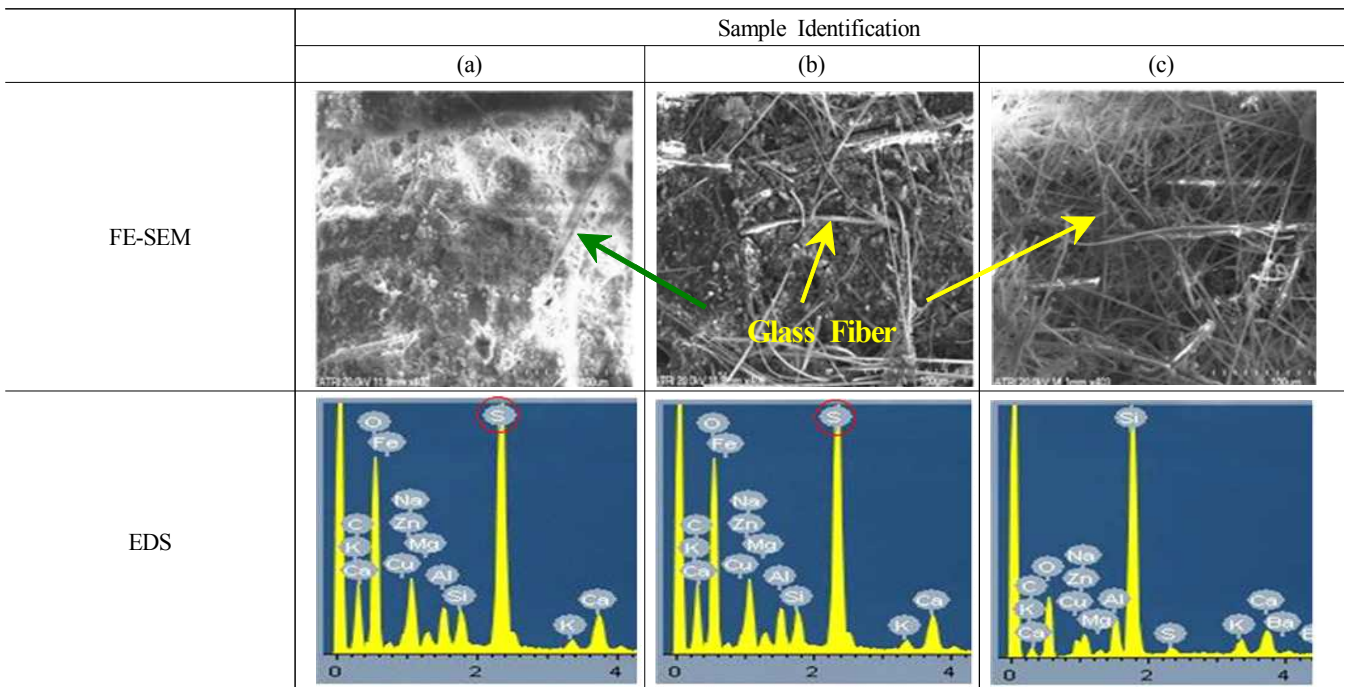


Figure 8. FE-SEM photographs and EDS spectra for the remnants of main filters in (a) the more severely failed, (b) the less severely failed, and (c) the unfailed.

fine particles, showing no fine lines. The main filter in FE-SEM photograph (b) is partly covered with these fine particles, showing some fine lines

Most of fine particles for two failed main filters belong to smaller than 10 μm in size. Compared with the particles from

outside of fuel filter, those of the main filter is even more fine. Maybe fine particles of main filter are considered as the main cause of blocking fuel filter. Figure 8(c) represents the remnants of the main filter for the unfailed do not exist, showing only many fine lines.





Sample I.D.	Before reaction	After reaction	Remarks
(a)			CuO (green) in solution
(b)			CuS (black) on the surface of copper

Figure 9. The reaction of copper wire (a) in the absence of sulfur and (b) in the presence of sulfur.

Figure 8 also shows EDS spectra for the remnants of the main filters in two failed main filters [(a) and (b)] and the unfailed fuel filter (c), respectively. As shown in Figure 8(c), the main filter of the unfailed is neat, showing only fine lines without any particles. A lot of fine lines were considered as glass fiber since it was commonly used as material of main filter in aircraft. Glass fiber was made up of chemical elements such as Mg, Si, Al, Ca, K, and Na. Chemical elements of the unfailed main filter corresponds to those of glass fiber. As shown in EDS spectra of Figures 8(a) and (b), it was found that chemical elements except sulfur for two failed main filters was corresponding with those of glass fibers. Therefore, chemical component of dark brownish impurities for two failed main filters was identified to sulfur.

In summary, the main filters of two failed fuel filters, which were more severe or less severe were filled with a number of fine particles. These fine particles were identified to sulfur. Therefore, sulfur in main filter was thought as the main cause of blocking fuel filter.

3. Identification of the Reduced or Oxidized Sulfur

To identify the influx pathway of sulfur from the fuel tank, Orsat method is applied.⁴ This method is generally used in measuring the purity of pilot's breathing oxygen. In base-buffer solution, the copper wire reacts with oxygen and changes colorless to blue since copper oxide is formed. Similarly, in acid buffer solution if sulfur instead of oxygen exists, there will be two types of colors. In reduced sulfur, the surface of copper wire will be changed into black color, resulting in the production of copper sulfide (CuS). If sulfur exists as the oxidized

forms such as SO_2 , SO_3 , and SO_4^{2-} , a black product will not be produced, only making copper sulfate (CuSO_4) as blue color in aqueous solution.

Figures 9(a) and (b) show the reaction of copper wire in the absence or presence of sulfur in acid buffer solution. Figure 9(a) indicates that the copper reacts with oxygen dissolved in water in the absence of sulfur and finally produces copper oxide (CuO). In this case, the color of the surface on copper wire was not changed, only changing the color of solution into green. Figure 9(b) uses the remnants from the main filter of the more severely failed fuel filter. The remnants are soaked into distilled water and controlled at pH 4.0 by acid buffer solution. Figure 9(b) shows that the copper reacts with sulfur and produces copper sulfide (CuS). Since sulfur was in reduced state as sulfide (S^{2-}), copper sulfide will be produced on the surface of copper wire. Thus, the color of the surface on the copper wire was changed into black. It was meant that sulfur was in the reduced state, not the oxidized.

4. The Source of Sulfur as the Blocking Material

When considered as reduced state of sulfur, there are two possibilities of influx pathway for it. one is from Indonesian JP-4 fuel and the other is from integral fuel tank sealant.

One may be considered that JP-4 fuel offers the cause of blocking fuel filter. The concentration of sulfur in crude oil is typically between 0.05 and 5.0 wt%, although values as high as 13.9 wt% have been reported.⁵ In general, the distribution of sulfur in crude oil is such that the proportion of sulfur increases along with the boiling point of distillate fraction. As a result, the higher the boiling range of the fuel

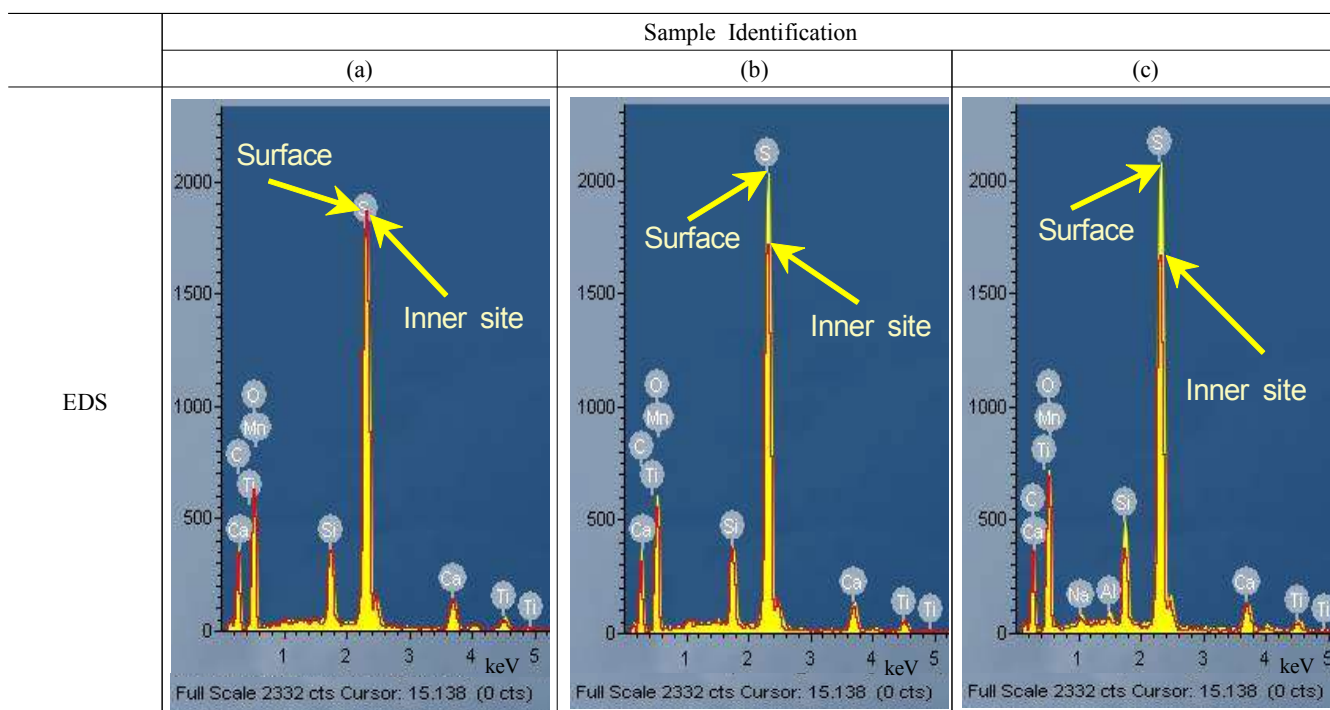


Figure 10. EDS spectra of sulfur at both the inner site and surface after aging according to the mixing ratios of (a) 100/10, (b) 100/20, and (c) 100/40 in Part B/Part A, respectively.

the higher the sulfur content will tend to be. Indonesian JP-4 fuel has been used in the failed aircraft. The total percentage of sulfur by weight in JP-4 fuel is measured by a total sulfur determinator. It is found that the sulfur content is about 0.078 ± 0.003 wt%, meeting specification of max. 0.400 wt%. Most of the sulfur compounds in fuel exist as reduced state such as thiols, sulfides, and thiophenes and are soluble in fuel.⁶ Upon combustion, sulfur can contribute to air pollution and engine corrosion in the forms of particulate material and acidic gases such as sulfur dioxide.⁵ To reduce sulfur-related effects and meet the regulation of the level of sulfur, sulfur must be removed from fuel during the refining process. From the result, it is found that the sulfur in JP-4 fuel of aircraft must be eliminated effectively. Therefore, sulfur in fuel is not considered as the blocking material of fuel filter.

The other may be thought that an integral fuel tank sealant offers the cause of blocking fuel filter. An integral fuel tank sealant that is commonly used is a manganese dioxide cured polysulfide compound. As given in Table 1, tank sealant is made up of two separated parts in liquid paste form, Part A and Part B. Part A contains ingredients such as MnO_2 as a curing agent, butyl benzyl phthalate as a plasticizer, carbon black, and an accelerator. Part B includes ingredients such as polysulfide polymers with the terminal thiol end groups (-SH) on both sides, fillers (CaCO_3 and TiO_2), toluene, and ethyl acetate.

Although an accelerator is classified as trade secret of the manufacturer, it is thought that only an accelerator of Part A contains sulfur. Whether Part A contains sulfur or not must be identified to trace the blocking material. Sulfur in Part A was identified and quantified with EDS. It was found that Part A contained about 3.0 wt% sulfur as described in note of Table 1. An accelerator is considered as chemical containing sulfur.

Polysulfide polymers of Part B are a class of chemical compounds containing chains of sulfur atoms. They are commonly used as sealants, caulks, gaskets, O-rings, and cements for insulating glass and fuel tanks because of an excellent resistance for fuel. Since both an accelerator of Part A and polysulfide polymer of Part B include sulfur, it was doubted that sulfur blooming resulted from an excessive loading of Part A or Part B during manufacturing. Blooming occurs only when a chemical is readily crystallizable, has a limited solubility in the compound, and is present in the compound at levels exceeding the solubility limit.⁷ So it is performed to know the effects of sulfur migration to surface on mixing ratios of Part B to Part A through an accelerating experiment.

Figures 10(a), (b), and (c) represent EDS spectra showing differences of the peak height of sulfur at both inner site and surface after aging according to the mixing ratios of 100/10, 100/20, and 100/40 in Part B/Part A, respectively. Table 3 represents the relative abundance of migration of sulfur to surface calculated from the peak height, on the basis of peak

Table 3. The Relative Abundance by Migration of Sulfur to Surface at both the Inner Site and the Surface After Aging for Each Compound

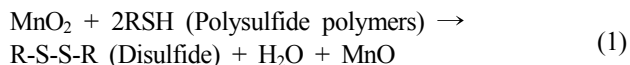
Ratios of Part B/Part A	Peak height at the inner site	Peak height at the surface
100/10	10.2 (100)	10.2 (100)
100/20	9.5 (100)	11.2 (118)
100/40	9.2 (100)	11.6 (126)

Numbers in parenthesis represent the relative abundance calculated from the peak height, based on peak height (100) at the inner site after aging for each compound.

height (100) at the inner site after aging for each compound. The results showed that migration of sulfur to surface was increased with the increment of loading of Part A and the relative abundance of migration was increased with the order of 100/10, 100/20, and 100/40 in Part B/Part A, respectively.

In the case of mixing ratio of 100/10 in Part B/Part A, an EDS spectrum showed that there was no difference of sulfur concentration between inner site and surface after aging, meaning no migration of sulfur to surface. Polysulfide polymers with the terminal thiol end groups were cured by the oxidation

of two end thiol groups in the presence of MnO₂.⁸⁻¹⁴ As a result, disulfide bond was formed. The curing process can be simply described with eq. (1).



Almost all sulfur within polysulfide polymers (Part B) was consumed in the formation of disulfide bond (~S-S~) by the oxidation reaction (curing) of thiols. This means that unbound (free) sulfur from polysulfide polymers is not produced before/after curing. Therefore, that is why there is no migration of sulfur to surface in excess of Part B.

A manganese dioxide functions as a curing agent of thiol in polysulfide polymer.⁷ Curing system of MnO₂/an accelerator of Part A can accelerate the cure rate of the sealant at the initial stage. Unlike polysulfide polymers, an accelerator can accelerate only cure rate and does not participate in chemical bond. After curing, it can migrate to surface by diffusion. An excessive loading of Part A can include much more accelerators containing sulfur in sealing compound. Accelerators migrate to surface and bloom at the surface. So the results

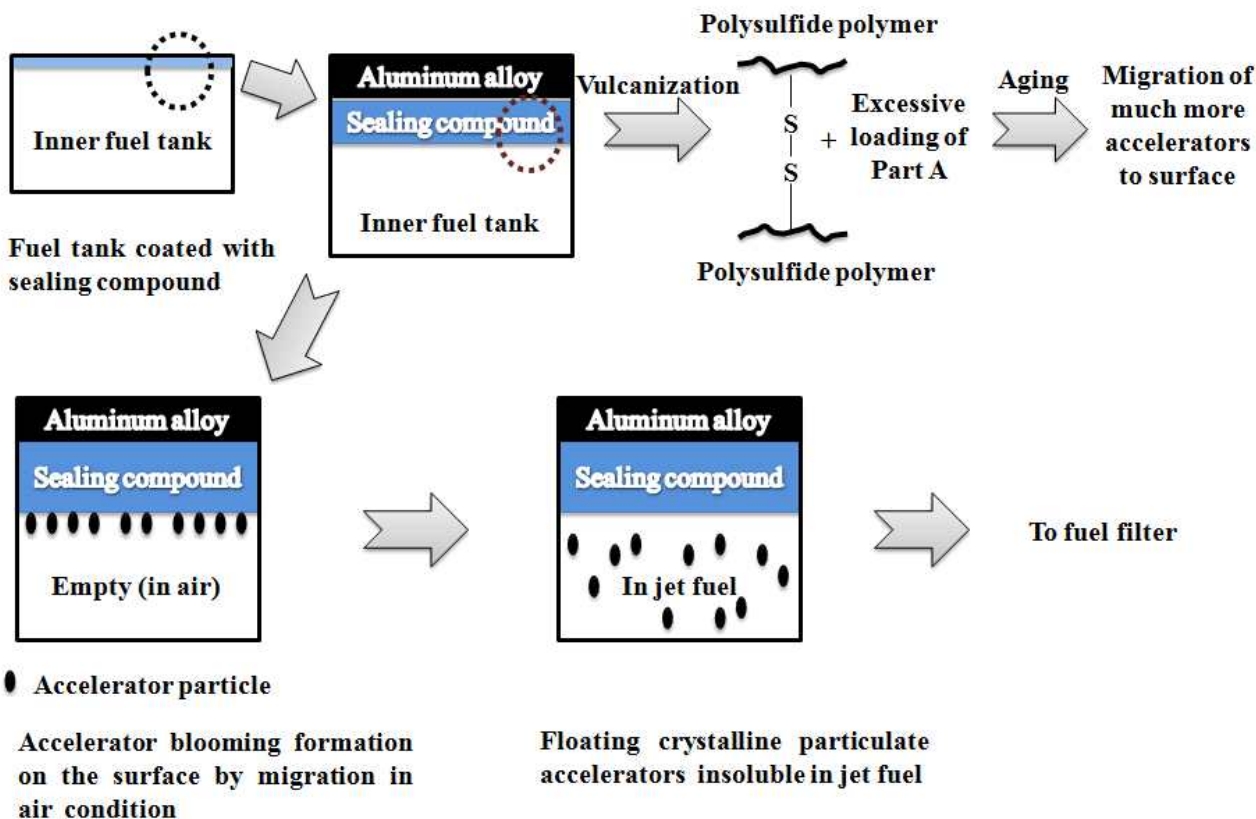


Figure 11. A mechanism for the formation of the blocking material by an accelerator blooming in fuel tank.

showed that migration of sulfur to surface was increased with the increment of loading of Part A. Generally, blooming materials are known as sulfur, accelerators, antioxidants, anti-ozonants, plasticizers, oil, and zinc stearate.^{7,15} Maybe it is thought that an accelerator blooming can be caused by an excessive loading of Part A during manufacturing.

Like most of accelerators, an accelerator of Part A in tank sealant also includes some elements such as C, N, S, and O. Until now, sulfur identified with EDS must be considered as one of an accelerator not pure sulfur because sulfur from an accelerator can be seen like pure sulfur in EDS spectra. Thus, an accelerator from Part A was considered as the blocking material of fuel filter

5. A Mechanism for the Formation of the Blocking Material by an Accelerator Blooming in Fuel Tank

Figure 11 indicates a mechanism for the formation of the blocking material by an accelerator blooming in fuel tank. As mentioned previously, blooming material as an accelerator can be produced by both the excessive loading of Part A and aging. As the vulcanizate cools after vulcanization, accelerator particles will crystallize and grow within the bulk of sealing compound. As the crystals grow within the bulk of the rubber, regions of strain will be set up around the crystal. These regions increase as the crystals grow until no further crystallization can occur. However, at the surface of the sealing compound, there will be much less strain and crystals will continue to grow, resulting in a lower soluble concentration of compound close to the surface. This, in turn, will lead to migration of the soluble compound from the bulk of the sealing compound in an attempt to remove the solute concentration gradient. Crystals in the bulk will redissolve to restore the bulk solubility concentration which will maintain the gradient. Migration will continue until all the bulk crystals have dissolved and there are a mass of crystals on the surface. It is known that the migration rate of antioxidants is increased by rising temperature.¹⁶

If fuel tank is empty instead of filling up fuel, migration to surface of accelerator will be more accelerated, together with the increasement of temperature. In case of filling up fuel, migration of accelerator may be even more decreased because of preventing fuel from coming out. During manufacturing, the fuel tank was empty. So migration to surface of accelerator within sealing compound in air condition was continuously increased, together with a cumulative effect by rise in temperature. Eventually much more accelerators were bloomed on the surface. Crystalline accelerators on the surface were insoluble in non-polar JP-4 fuel because of their polarity. For flying if fuel tank is filled with JP-4 fuel, a lot of crystalline accelerators on the surface will be detached and floated

in JP-4 fuel. These floated fine accelerator particles could not be filtered by the main filter of fuel filter. Therefore, blocking of fuel filter resulted in an accelerator released by an accelerator blooming in air condition.

IV. Conclusions

The cause of blocking fuel filter in aircraft was investigated using various analytical techniques such as FT-IR microscopy, FE-SEM/EDS, and total sulfur determinator. Before disassembling two failed fuel filters, extracts from outside of two failed fuel filters were separated into a yellow-brownish liquid and blackish particles by filter paper. After evaporating solvent, a yellow-brownish liquid was identified as an ester oil and blackish particles were identified as sulfur. But both an ester oil and sulfur particles were less effective on blocking fuel filter because of minor quantity. After disassembling two failed fuel filters, the remnants of main filters were identified to sulfur in fine particles and were much more effective on blocking fuel filter because of much quantity. It was found that sulfur existed in the reduced state as sulfide (S^{2-}). Sulfur was identified as one of an accelerator from Part A of the integral fuel tank sealant. So the blocking material of fuel filter was considered as an accelerator and resulted from excessive loading of Part A in the integral fuel tank sealant during manufacturing. And it was concluded that blocking of fuel filter resulted in an accelerator released by an accelerator blooming phenomenon in air condition.

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