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Cause of Fuel Leakage from the Inner Piston Packing of Afterburner Fuel Pump in an Aircraft J85-GE-21 Turbojet Engine

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전투기 J85 - GE - 21 터보제트 엔진 후기 연소기 연료펌프의 내부 피스톤 패킹 연료 누출 원인

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ABSTRACT : Most of military supersonic aircraft use an afterburner. It plays an important role in performing unusual duties for supersonic flight, takeoff, and combat situations. Recently, repetitive fuel leakage from the inner piston packing rubber of afterburner fuel pump in an aircraft J85-GE-21 turbojet engine has happened. These failures have only happened in one manufacturer's parts of two manufacturers. Thus, the cause of these failures was investigated through the comparative analysis for both the failed and the unfailed with two different manufacturers using various analysis methods. The failure analysis was performed using analysis methods such as swelling or swelling ratio, total sulfur content, polymer identification, loading and surface area of carbon black, and hardness. Consequently, the main cause of this failure was identified to be insufficient loading of carbon black as a reinforcing agent, together with small surface area of carbon black and somewhat low sulfur content.

요 약 : 대부분 군사용 초음속 전투기는 후기 연소기를 사용한다. 후기 연소기는 초음속 비행, 이륙, 전투 상황에 대해 비상 임무 수행을 가능하게 하는 중요한 역할을 한다. 최근 전투기 J85-GE-21 터보제트 엔진 후기 연소기 연료펌프의 내부 피스톤 패킹고무에서 반복적인 연료 누출 결함이 발생하였다. 이러한 결함은 두 제조사 중 한 제조사의 부품에서만 발생하였다. 따라서, 결함발생 원인을 제조사가 상이한 정상품 및 결함품에 대하여 다양한 비교 분석방법을 통하여 조사하였다. 결함분석에는 팽윤 또는 팽윤도, 총 황함량, 폴리머 확인, 카본블랙 함량 및 표면적, 경도와 같은 분석방법이 적용되었다. 결론적으로, 반복적인 연료 누출 결함의 주요 원인은 보강제 카본블랙의 함량 미달로 확인되었으며, 더불어 표면적이 작은 카본블랙과 함량이 낮은 황 적용이 결함원인에 부가적인 영향을 준 것으로 확인되었다.

Keywords : fuel leakage, aircraft, afterburner pump, failure analysis, carbon black

I. Introduction

An afterburner is an additional component present on some jet engines, mostly military supersonic aircraft. It is an extended exhaust section containing extra fuel injectors and is a simple type of ramjet because the jet engine upstream before the turbine uses little of the oxygen it ingests. When it is turned on, fuel is injected through afterburner fuel pump and igniters are fired. It does produce remarkably enhanced thrust as well as a very large flame at the back of the engine. Its purpose is to provide an increase in thrust, usually for supersonic flight, takeoff, and combat situations. Figure 1 shows afterburning for supersonic flight of F-5 aircraft. This exhaust flame may show "shock diamonds", which are caused by shock waves formed due to slight differences between ambient pressure and the exhaust pressure. These unbalances cause oscillations in the exhaust jet diameter over distance and cause the visible banding where the pressure and temperature is highest.

Afterburning is achieved by injecting additional fuel into the jet pipe downstream of the turbine. It brings very high fuel consumption for a short periods. Pilots can activate and deactivate afterburners in-flight. Jet engines are referred to as operating "wet" when afterburning is being used and "dry" when not.[1-2] An engine producing maximum thrust wet is at maximum power, while an engine producing maximum thrust dry is at military power.

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Figure 1. Afterburning for supersonic flight of F-5 aircraft.

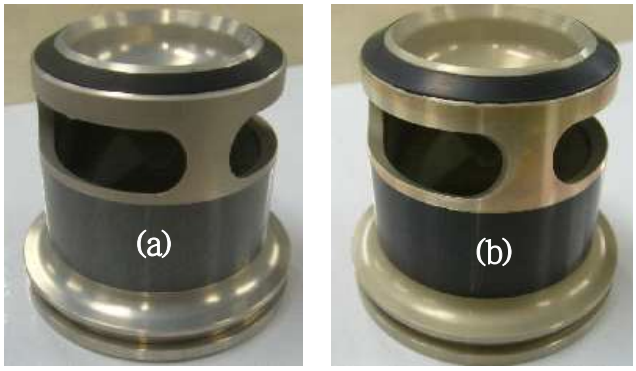

Figure 2. The inner piston packing parts for afterburner fuel pump of (a) the failed and (b) unfailed components.

For an aircraft jet engine with afterburner, both fuel pumps for the base engine and for the afterburner are integrated in the jet engine's control system. When the fuel pump for the afterburner is turned off, fuel is injected into the base fuel pump. At this time an inner piston packing rubber prevents fuel from flowing into the fuel pump for the afterburner. On the contrary, when the fuel pump for the afterburner is turned on, fuel is injected into the afterburner fuel pump. At this time an inner piston packing is opened to send much fuel to the turbine. We have used two kinds of products with different manufacturers for afterburner fuel pump. One of them has caused problems of the fuel leakage in afterburner fuel pump of J85-GE-21 turbojet engine. Moreover, the repetitive failures from the inner piston packing of afterburner fuel pump has occurred.

In this study, the repetitive fuel leakage of afterburner fuel pump was investigated through the comparative analysis for two products with different manufacturers using various analysis methods. The analytical techniques were used with FT-IR microscopy (IlluminatIR II, Smiths), thermogravimetric analyzer (Pyris-1, Perkin Elmer), nitrogen surface analyzer (Gemini II 2370, Micrometrics), total sulfur determinator (SC-432DR, LECO), and Shore A durometer (CL-150, Asker).

II. Experimental

1. The failed and unfailed samples

As shown in Figure 2, two kinds of inner piston packing parts for afterburner fuel pump in the J85-GE-21 turbojet engine have been supplied by two different companies. one is manufactured by Kampton in USA and the other is produced by BF Goodrich in Canada. One is an abnormal product because of repetitive fuel leakage from the inner piston packing part, called it the failed and the other is a normal product, called it the unfailed.

2. Swelling

Swelling test was performed in the packed rubber on afterburner fuel pump (ABP) for the failed and unfailed samples which have been used. Swelling indicates that the ability of rubber to absorb fuel or solvent. Generally, the more swelling increases the more fuel resistance decreases. To know some degree of swelling in fuel, two samples were completely soaked in 500 mL beaker filled with jet propellant-8 (JP-8) fuel for 3 days. After finishing swelling, two samples were photographed to compare differences.

To evaluate swelling quantitatively, the packed rubbers were cut into appropriate dimension and then the swelling ratio (Q) was measured by the method of equilibrium swelling for the failed and unfailed rubbers.[3] About 2.36 to 2.79 g of samples was weighed. They were immersed into *n*-hexane for 3 days at room temperature and the weights of swollen samples were measured. The swelling ratio (Q) was calculated by the equation, $Q = (W_s - W_u)/W_u$, where W_s and W_u are weights of the swollen and unswollen samples. The swelling ratios for two samples were measured three times and averaged.

3. Determination of total sulfur content

The total percentage of sulfur by weight was determined by infrared absorption using total sulfur determinator. About 0.15 to 0.16 g of samples was weighed, measured three times, and averaged.

4. Polymer identification

Two samples were cut into $1mm^3$ in size and about 0.2 g of samples was put into vials. Samples were extracted to eliminate organic matters in acetone for 4 h and dried in oven at 80℃. Samples were dissolved in 0.8 mL of ODCB (*ortho*-dichlorobenzene, b.p. 185℃) at the boiling temperature for 1 h. Because this chemical is a very toxic, all processes must be performed in fume hood. During dissolution, crosslinking

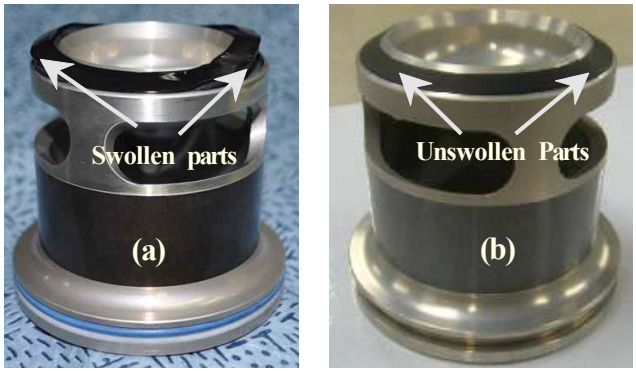

Figure 3. Swelling of (a) the failed and (b) the unfailed packing rubber parts in JP-8 fuel.

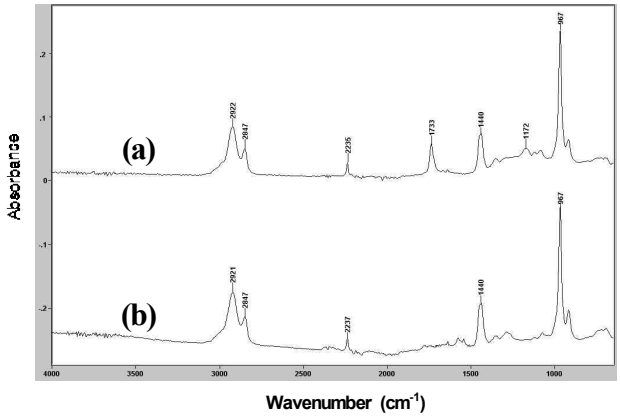

Figure 4. FT-IR spectra for packing rubbers of (a) the failed and (b) unfailed components.

bonds between rubber chains are broken. Then, free polymers are extracted from samples. Free polymer is defined as one not bound by polymer-filler interaction but bound by only both polymer-polymer physical interaction and chemical cross-linking bond by sulfur. Free polymer solution in ODCB is coated on glass with IR reflecting coat and throughly dried by heat gun. They were used on FT-IR measurement. The IlluminatIR II system is equipped with diamond attenuated total reflectance (dATR) objective and absorption reflectance objective (ARO). FT-IR spectra in reflection absorption mode were taken on thin film, using FT-IR microscopy. The samples were scanned from 400～4000 cm^{-1} with a resolution 4 cm^{-1} and average of 32 scans for each sample was taken for the measurement.

5. Determination of carbon black content

The relative rubber compositions of organic matter, polymer, carbon black, and ash (metal oxide) for the inner piston packing rubber were determined using a thermogravimetric analyzer (TGA).[4] About 10 to 20 mg of samples was weighed. TGA measures the amount of change in the mass of a sample as a function of time (or temperature) in a controlled atmosphere. The analysis conditions of TGA were as follows (the initial temperature is 30℃).

1. Holding at 30℃ for 1.0 min.
2. Increasing 30℃ to 550℃ at the rate of 20℃/min.
3. Holding at 550℃ for 10 min and increasing 550℃ to 750℃ at a rate of 20℃/min.
4. Holding at 750℃ for 20 min.

TGA was performed under N_2 for steps (1) and (2) and was performed under air for step (3) and (4). The content of organic matter was calculated by the weight difference of sample between 30℃ and 300℃. The amount of polymer was determined by the weight difference between 300℃ and 55 0℃. The amount decreased for the step (3) was determined as the content of carbon black for the inner piston packing rubber. The ash content was the remnant of step (4).

6. Determination of surface area of carbon black

6.1 Collection of carbon black from vulcanizate

Carbon black from vulcanizate could be collected by pyrolysis using a furnace. Samples were placed in chamber of furnace, heated at the rate of 100℃/min to 650℃, maintained for 30 min, and cooled at the rate of 150℃/min to 25℃. Collection of carbon black was performed in N_2 atmosphere.

6.2 Measurement of nitrogen surface area (N_2SA)

Carbon black collected from vulcanizate was treated with 1% HCl solution to eliminate inorganic component such as ZnO, washed with distilled water, and then dried at 125℃ oven for 30 min. About 0.15 g of carbon black was weighed and degassed at 200℃ oven for 2 h at the degassing station of nitrogen surface analyzer.[5] After carbon black was well degassed, the adsorption and desorption processes were performed. The integration area under the desorption curve was obtained to calculate the surface area.

7. Hardness

Hardness was measured using Shore A durometer. Durometer hardness scale runs from 0 for zero extension to 100 for full extension. Hardness represents a relatively hard degree on the basis of glass hardness (100).[6]

III. Results and Discussion

1. Swelling

Figure 3 shows swelling of the failed packing rubber (a) and unfailed packing rubber (b) in JP-8 fuel, respectively. Swelling indicates the ability of rubber to absorb fuel. As swel-

Table 1. Swelling Ratio of the Failed and Unfailed Packing Rubbers

Sample I.D.	Sample No.	Sample weight (g)		Average swelling ratio (%)
		Unswollen, W_u	Swollen, W_s	
The failed	1	2.7936	2.9928	7.09 ± 0.04
	2	2.7856	2.9833	
	3	2.5786	2.7605	
The unfailed	1	2.5989	2.6245	0.96 ± 0.03
	2	2.3698	2.3914	
	3	2.7596	2.7869	

Table 2. Total Sulfur Content for the Failed and Unfailed Packing Rubbers

Sample I.D.	Total sulfur content, wt%
The failed	0.400 ± 0.007 (0.91)
The unfailed	0.591 ± 0.001 (1.18)

Numbers in parenthesis represent phr (parts per a hundred rubber part) calculated from eq. (1).

ling increases, the fuel resistance decreases.[6] The results showed that the failed packing rubber (a) was swollen in some parts but the unfailed packing rubber (b) was not swollen at all.

To estimate quantitatively both of them, swelling ratios were measured. Two samples were cut into rectangular forms and put into *n*-hexane at room temperature for 3 days. The swelling ratio was calculated by the equation, $Q = (W_s - W_u)/W_u$, where W_s and W_u are weights of the swollen and unswollen samples, respectively. As shown in Table 1, the average swelling ratios of the failed and unfailed samples were 7.09 and 0.96%, respectively. The results showed that swelling of the failed packing rubber was much higher than that of the unfailed one. Swelling was closely related with physical properties such as tensile strength, hardness, elongation, compression set, and crosslink density. In general, swelling increases with decrement of tensile strength, hardness, crosslink density and increment of elongation and compression set.[7] From these results, it was concluded that the failed was very weak to fuel resistance.

2. Total sulfur content

To know the effect of swelling on sulfur as a cross-linking agent, the total percentage of sulfur by weight for the failed and unfailed packing rubbers was determined by a sulfur determinator. It was well known that the swelling decreases with increase of crosslink density. The crosslink density increases with increment of total sulfur content to some extent.[8] The results were given in Table 2. It was found that total sulfur content of the failed was about 0.2 wt% lower than that of the unfailed, meaning lack of 33% on the basis of the unfailed. However, it was considered that somewhat low total sulfur content for the failed did not affect significantly crosslink density, meaning no direct effect on fuel leakage of the inner piston packing rubber.

3. Polymer identification

FT-IR spectra of the failed and unfailed packing rubbers are represented in Figures 4(a) and (b), respectively. Figure 4(a) shows the same absorption patterns with the unfailed packing rubber except peaks at 1733 and 1172 cm^{-1} indicating carboxyl group (-COO). It may be thought that these peaks of the failed packing rubber are the characteristics of carboxylated nitrile butadiene rubber (XNBR) as represented in Table 3.[9] Figure 5 shows microstructures of XNBR. XNBR has been used to provide better strength properties, especially abrasion resistance than NBR. XNBR has extra strength properties because two carboxylate groups between inter-molecules are crosslinked through ionic reaction with divalent metallic oxides, such as zinc oxide (ZnO).[6] In XNBR, there are two types of cross-links such as carboxylate and sulfur.

As shown in Figure 4(b), peaks at 2921, 2847, and 1440 cm^{-1} are the characteristic ones of methyl ($-CH_3$) and methylene group ($-CH_2-$), peak at 2237 cm^{-1} indicates one of nitrile group ($-C\equiv N$), peak at 967 cm^{-1} is one of *trans*-1,4 butadiene (*trans*-1,4 BD), and very weak peaks at 739 cm^{-1} and 910 cm^{-1} are *cis*-1,4 butadiene (*cis*-1,4 BD) and 1,2 butadiene (1,2 BD), respectively. These peaks of the unfailed packing rubber show the characteristics of nitrile butadiene rubber (NBR) as

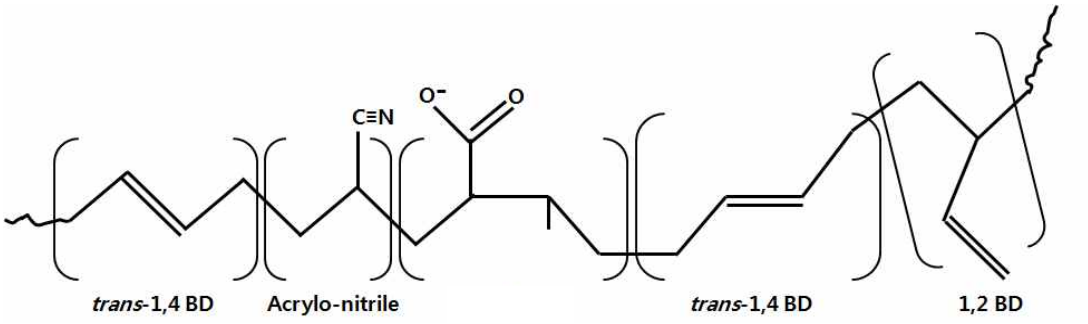

Figure 5. Microstructures of XNBR.

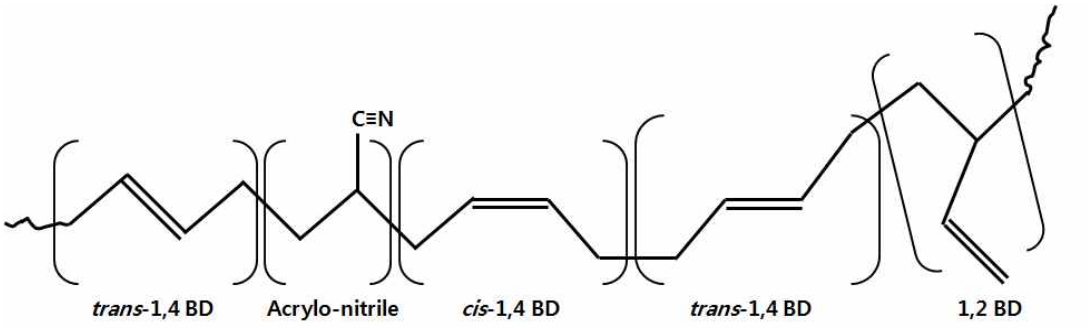

Figure 6. Microstructures of NBR.

Table 3. Characteristic FT-IR Peaks for the Failed and Unfailed Packing Rubbers

Sample I.D.	Polymer	FT-IR band, cm^{-1}	Chemical structure
The failed	XNBR	2922, 2847, 1440	CH_3-(Methyl), -CH_2-(Methylene)
		2235	-C≡N(Nitrile)
		1733	C=O(Carbonyl)
		1172	C-O Bond
		967	*trans*-Butadiene
The unfailed	NBR	2921, 2847, 1440	-CH_3(Methyl), -CH_2-(Methylene)
		2237	-C≡N(Nitrile)
		967	*trans*-Butadiene

indicated in Table 3. Figure 6 shows microstructures of NBR. NBRs belong to the class of specialty elastomers that offer a broad range of oil resistance properties. The polar nitrile group (-C≡N) in the NBR backbone chain greatly contributes to oil resistance. Nitrile butadiene rubber (NBR) family is most notable for its high resistance to oils, fuels, and other chemicals.[7,10] It has wide temperature range from －51 to 125℃. In the aerial area, NBR is commonly used in fuel and oil handling hose, seals, O-rings, and gaskets. NBR is produced in an emulsion polymerization and copolymer having acrylonitrile (ACN)/butadiene (BD) monomer ratios in the range of 18/82 to 45/55. ACN/BD monomer ratios are varied for specific oil, fuel resistance, and low temperature requirements. NBR with higher ACN content improves solvent, oil and abrasion resistance, along with higher glass transition temperature.

In general, because XNBR and NBR have an excellent resistance for oil or fuel, they are applied to O-rings, seals, gaskets, and fuel hoses. From the results, it could be considered that XNBR application of the packing rubber for the failed was not the cause of fuel leakage.

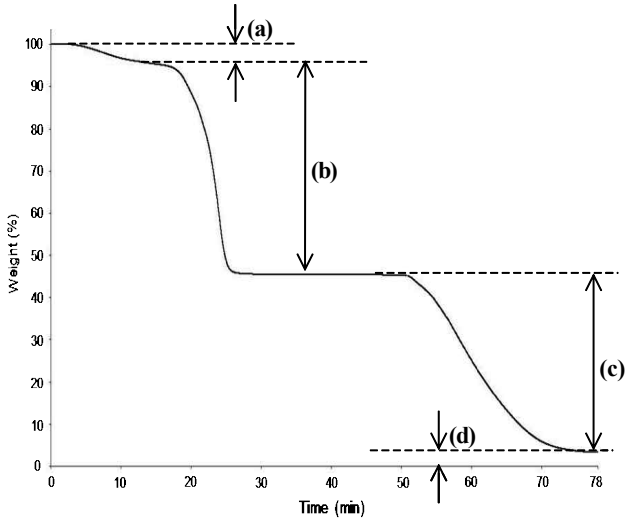

Figure 7. TGA curve of the failed packing rubber. (a) organic matters, (b) polymer, (c) carbon black, and (d) ashes.

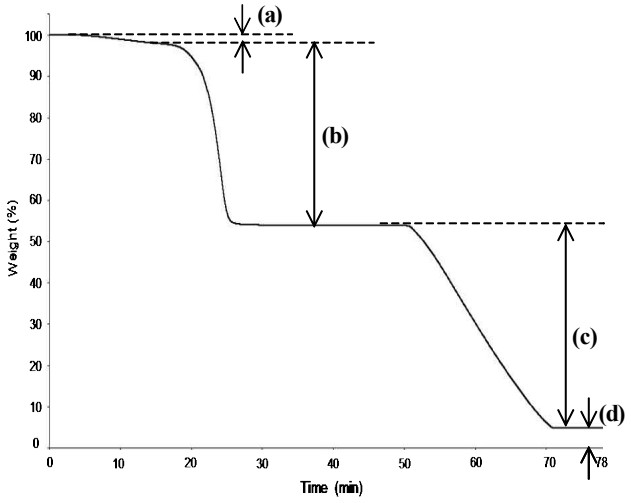

Figure 8. TGA curve of the unfailed packing rubber. (a) organic matters, (b) polymer, (c) carbon black, and (d) ashes.

4. Carbon black content

Carbon black is commonly added to rubbers to improve some specific physical properties such as tensile strength, hardness, abrasion resistance, and fuel resistance. It is well known that the effect of increasing loading or surface area on fuel resistance increases.[11] To know the cause of fuel leakage, the contents of carbon black for both the failed and unfailed samples were measured. In many cases the percentage of carbon black in a rubber vulcanizate can be determined by TGA method. In addition, rubber compositions which consist of organic matters, polymers, carbon black, and ashes can be measured quantitatively in specific condition. Rubbers extracted by acetone were decomposed in nitrogen between 30℃ and 550℃

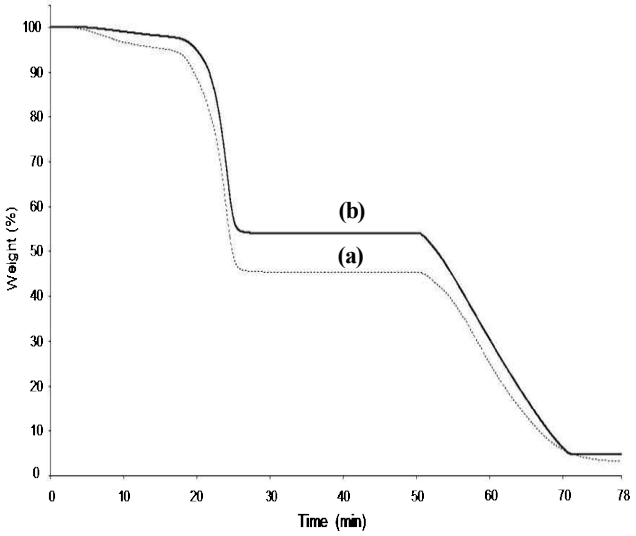

Figure 9. TGA curves of (a) the failed and (b) unfailed packing rubbers.

and in oxygen between 550℃ and 750℃. It was measured in 100 wt% at time-dependent. The rubber compositions of organic matters, polymer, carbon black, and ash for the failed and unfailed packing rubbers by TGA were given in Figures 7 and 8, respectively. Organic matters (organic components including low molecular weights) are evaporated or decomposed below 300℃ under nitrogen, while most of polymers are decomposed at 300～550℃ under nitrogen. Carbon black is burnt out at 550～750℃ under air, emitting CO_2 gas. In these temperature ranges, the percentage of carbon black could be determined. Components remained after combustion at 750℃ are ashes (metal oxides). TGA curves of the failed and unfailed packing rubbers were shown in Figure 9. As shown in Table 4, the percentages of organic matters, polymer, carbon black, and ashes for the failed and unfailed rubbers were 4.69, 49.9, 42.1, and 3.31 and 1.97, 44.1, 49.2, and 4.73%, respectively. The conversion of weight % into phr (parts per a hundred rubber part) can be expressed as equation (1).

$$\text{phr (carbon black)} = [\ \text{carbon black (wt\%)} / \text{polymer (wt\%)}\ ] \times 100 \quad (1)$$

Using equation (1) the carbon black content in phr could be calculated. The content of carbon black for the failed and unfailed is 84 and 112 phr, respectively. It is found that the content of carbon black for the failed is approximately 30 phr less than that of the unfailed. Generally, It was well known that as loading of carbon black increases, hardness increases, tensile strength decreases with increasing trends in the early stages, elongation decreases, and the fuel resistance increases.[12-14] Maybe it was

Table 4. Rubber Compositions by TGA

Sample I.D.	Rubber compositions, wt%			
	Organic matters	Polymer	Carbon black	Ash
The failed	4.69 (9.38)	49.9 (100)	42.1 (84.4)	3.31 (6.63)
The unfailed	1.97 (4.43)	44.1 (100)	49.2 (111.6)	4.73 (10.75)

Numbers in parenthesis represent phr (parts per a hundred rubber part) calculated from eq. (1).

Table 5. Specific Surface Area of Carbon Black Collected from the Failed and Unfailed Rubber Vulcanizates

Sample I.D.	Specific surface area, m^2/g
The failed	36.4
The unfailed	42.0

Table 6. Hardness for the Failed and Unfailed Packing Rubbers

Sample I.D.	Hardness
The failed	61 ± 1.0
The unfailed	73 ± 1.5

considered that much lower carbon black content for the failed was the main cause of repetitive fuel leakage.

5. Surface area of carbon black

As previously stated, surface area of carbon black can affect fuel resistance. The more surface area of carbon black increases, the more fuel resistance increases. Likely, to know the cause of fuel leakage, surface areas of carbon black for the failed and unfailed samples were measured. Table 5 represents the specific surface area of carbon black collected from vulcanizates of the failed and unfailed samples. Specific surface areas of carbon black for the failed and unfailed samples were 36.4 and 42.0 m^2/g, respectively. It was shown that carbon black grades of the failed and unfailed samples were similar to N650 and N550, respectively. It was inferred that relatively low surface area of carbon black for the failed sample might have some effects on the cause of fuel leakage.

6. Hardness

Samples detached from the packed rubber are used for hardness measurement. The Shore A durometer is used for hardness. The results are represented in Table 6. It is measured that hardness for the failed is approximately 12 less than that of the unfailed. Carbon black is a filler used as a reinforcing agent for polymer. Generally, as the loading of carbon black increases the hardness increases. Therefore, it is thought that low hardness of the failed greatly results in the insufficient loading of carbon black.

IV. Conclusions

The repetitive leakage of JP-8 fuel from the inner piston packing rubber of afterburner fuel pump in an aircraft J85-GE-21 turbojet engine was investigated through the comparative analysis for both the unfailed and the failed samples with different manufacturers using various analysis methods of swelling or swelling ratio, total sulfur content, polymer identification, the loading and surface area of carbon black, and hardness. Compared to the unfailed sample, the failed sample was shown that high fuel swelling or solvent swelling ratio, somewhat low total sulfur content, much less carbon black content in rubber compositions, low surface area of carbon black, and much lower hardness, although polymer for the failed and unfailed was identified to be a family of NBR. It means that high swelling of the inner piston packing rubber in JP-8 fuel was weak to fuel resistance and was closely related to fuel leakage. It was considered that high swelling resulted from mainly insufficient content (loading) of carbon black and partially low total sulfur content and low surface area of carbon black. Therefore, the main cause of repetitive fuel leakage was identified to be insufficient loading of carbon black as a reinforcing agent, together with a small surface area of carbon black and somewhat low total sulfur content.

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