ELASTOMER COMPATIBILITY TEST OF ALTERNATIVE FUELS USING STRESS-RELAXATION TEST AND FTIR SPECTROSCOPY

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ABSTRACT

Global efforts to reduce CO₂ emissions and to tackle the problem of depleting petroleum resources have stimulated the exploitation of alternative fuels in the aviation industry. One crucial aspect amongst others is to investigate the compatibility of alternative fuels with elastomeric materials currently used in gas turbine engines. However, little knowledge about this has been understood so far for commercial aircrafts under real engine conditions. This study combines Stress-Relaxation test and FTIR spectroscopy techniques to look at the effect of alternative fuels on O-rings made from different materials; such as nitrile, fluorocarbon and fluorosilicone. Results indicated that after immerged in fuels for a period of time while simultaneously being compressed at certain temperatures, the fluorocarbon O-rings showed minimum change in the eight types of fuels tested. This meant they are compatible with these fuels, with the nitrile O-rings changing the most. Furthermore, FT-SPK+20% hexanol caused the biggest relaxation in fluorosilicone O-rings but had the smallest effect on nitrile ones while all fuels presented similar behavior in fluorocarbon. FTIR spectrum analysis showed molecular composition changes are dependent on the reactions between different materials and fuels. For fluorosilicone O-rings, the absorbance reduction from 1150 to 1050 cm⁻¹ was caused by the breakdown of (Si-O-Si) while the formation of new O-H bonds enhanced the intensity from 3000 to 2800 cm⁻¹. For fluorocarbon O-rings, obvious increase in absorption could be found in the region from 1400 to 650 cm⁻¹, while from 3000 to 2800 cm⁻¹, the absorption decreased. Multiple linear regression analysis indicated a highly correlated relationship between the chemical structure changes and the force relaxation.

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INTRODUCTION

The kerosene fraction of crude oil has always been the preferred source of aviation fuel because it offers the best combination of performance, energy content, availability, ease of handling, and price. As the aviation industry is predicted to grow by up to 5% per year in the near future, concerns over the environmental impact and supply of fossil fuels have prompted the development of aviation kerosene from alternative sources [1, 2]. For example, a fuel, produced from natural gas or coal by Fisher-Tropsch process and blended with natural kerosene, has already been approved for use; and fuel produced from gas has been tested on a commercial flight and is in the final stages of approval [3].

Amongst other technical requirements which alternative fuels need to satisfy, one of the crucial "fit-for-purpose" properties is their compatibility with elastomeric seals, most commonly O-rings, in a gas turbine engine. O-rings are an elastomeric material which is squashed between two mating faces of a fuel system. The material deforms into the gap between the faces, and thus provides a seal between them [4]. However, the O-rings that are used, particularly the nitrile Orings creates a good seal because they swell in the presence of kerosene. When some alternative fuels are used, the O-rings either shrink or no longer swell to the volume that could provide a good seal [5-7]. As the use of an alternative fuel should not cause any change to an engine's component [8], it must therefore also be fully compatible with the existing Orings to prevent any fuel leakage, which could lead to catastrophic consequences.

The aim of this paper is to investigate the compatibility of three main types of O-rings; namely nitrile, fluorocarbon, and fluorosilicone, with alternative fuels. A novel combination of the Stress-Relaxation Test technique and Fourier Transform Infrared Spectroscopy (FTIR) was employed in this study. The O-rings were immerged in the fuels separately while being compressed in a continuous stress relaxation rig manufactured by Elastocon AB in order to simulate the real engine conditions. After the completion of the stress-relaxation process, the Orings were taken to perform chemical composition analysis by FTIR. In this way, the composition changes of O-ring materials caused by the fuels could be analyzed in the spectra. Furthermore, the multiple linear regression analysis was employed to explore the correlations of changes between the force relaxation and spectra. Data of stress-relaxation tests were presented as well as the IR spectra of each O-ring material. Chemical reasons for the O-ring composition changes were also discussed in this work.

NOMENCLATURE

 F_t Counterforce measured after the specified time (t) of the test (N)

 F_0 Initial counterforce measured 30 min after completing the compression (N)

BACKGROUND

The aviation industry demands the most from elastomeric materials, which requires the O-rings must be developed to meet certain specifications, such as resistance to fuel, heat and extreme temperatures [9]. The different types of elastomeric materials can be represented by nitrile (older aircraft), fluorocarbon (currently widely used) and fluorosilicone (the modern and future choice). Nitrile is the most widely used elastomer in the seal industry due to its good balance of desirable properties, high wear resistance and economic efficiency. The major limitations of nitrile are its poor weather resistance and moderate heat resistance. Fluorocarbon has excellent resistance to high temperatures (up to 204 degC) and a broader range of chemicals compared with any other elastomer; however, its sealing performance under low temperatures is also not favorable. Fluorosilicone combines most attributes of silicone which provides excellent performance at low temperatures (down to -73 degC) and good resistance to petroleum oils and fuels; but its poor physical strength and abrasion resistance restrict it to static seals [9].

It has been discovered that changing between a petroleumderived fuel and a synthetic fuel can cause elastomeric materials in the fuel system to shrink, leading to potential fuel leaks [10-14]. A drop from as little as 16% to 13% has been known to cause leakage [15]. This topic of research is particularly difficult to study as there are many types of alternative fuels and elastomeric materials used in sealing systems. With standard aviation kerosene their typical swelling properties are 20% (nitrile O-rings), 6-9% (fluorosilicone Orings) and 0.1-0.4% (fluorocarbon O-rings) respectively. However, they are all dependant on the aromatic content of the fuel [11, 12, 15]. The main cause for O-ring swelling is the ability of the fuel to penetrate into the O-ring material and remain there between the molecular structures; which increases the distance between them and creates swell [5]. Generally, the swelling ability of a material increases with increasing polarity and hydrogen bonding and decreasing molar volume. The paraffinic molecules in the FT fuel are relatively large and inert; however, aromatic compounds of similar molecular weight have both polar and hydrogen bonding and a smaller molar volume, which enhance the volume swell characteristics of a polymer [16]. This is also the reason why a minimum proportion (typically 8%) of aromatic compounds must to be added into current synthetic fuels, as fuels derived from FT process contain no or trace aromatics. A number of experiments have been done in investigating the different impacts of conventional and synthetic fuels on elastomers. Muzzell et al found that large swings in swell occurred for nitrile elastomers when switching between synthetic aviation fuels with and without aromatics. The swell volume increased with increasing the concentration of aromatics and was affected by the aromatic types [11, 12, 15]. Another evaluation of elastomer compatibility with Sasol Fully Synthetic Jet Fuel (FSJF) conducted by Moses and Roets [10] suggested nitrile O-rings were more sensitive to fuel chemistry than fluorocarbon and fluorosilicone O-rings, as they exhibited the largest changes in mass, volume and hardness after soaking in FSJF blends for a certain period of time. The focus of all these works was the relation between the aromatic content in the conventional or synthetic fuels and the swell volume of O-rings. The test method employed was to soak the O-ring materials into different fuels for a certain period of time under specific temperatures; and then compare the changes of physical properties of these O-rings, such as mass, volume, hardness, etc. However, these tests were all carried out using static immersion method, which meant no pressure was applied on the O-rings. Using this method to predict how the O-rings would perform in synthetic fuels under real engine conditions might be still unpredictable. In addition, the impact of synthetic fuels on O-rings could not be explained in a further level.

Stress relaxation is defined as the reduction of force required to maintain a given strain over time. Both physical and chemical processes occur during this process; physical processes dominate the stress relaxation process during short periods of time, while chemical processes are the main reasons for long time exposures in degradative environments. Degradation caused by chemicals may result in decrosslinking and/or chain scission, which would possibly reduce the counter force during stress relaxation test [17, 18]. When an O-ring is under pressure applied in the fuel system, stress relaxation process will occur and influence its sealing performance. It is important to gain further understanding of this phenomenon in order to prevent any possible fuel leakage of synthetic fuels in an engine.

FTIR technique has been preferred to identify the chemical and structural changes of elastomeric materials because of its fast scan speed and easy sample preparation [19-21]. The compatibility of some elastomeric materials with biodiesel has been investigated using FTIR. From the spectra obtained, researchers found that elastomers seemed to degrade more in biodiesel than petroleum-diesel as the former has more carboxylic groups [19]. Similarly, as the molecular structure information of a material sample will all be revealed in an IR spectrum, changes caused by degradation or chemical reaction could be found when compared with a new one.

EXPERIMENTAL DETAILS

Procedure

The equipment employed for the stress-relaxation test was the Elastocon Relaxation Tester EB 02. It has four rigs in a cell oven which all have the same specification for compression test. According to the test standard ISO 3384, test method "A" was used therefore the samples were compressed and all counterforce measurements were made at the test temperature [18]. The sample O-ring was inserted between two compression plates and compressed by 20% of its original size. Then, 150 mL of fuel was injected into the container to immerse the sample O-ring. Each rig contained one type of fuel, and Rig 4 was assigned as the reference fuel in each group. The test temperature was set at 30 degC in order to keep the rigs running safely. This is because the flash point of kerosene is around 38 degC. The counterforce and temperature of each rig were monitored and recorded continually throughout the experiment on a computer connected to the Elastocon. Normally the test period was one week, but may vary depending on how long it took to illustrate different relaxation trends between the various rigs.

When the stress relaxation tests finished, the sample O-rings were then taken to perform the FTIR analysis using Perkin Elmer Spectrum One Spectroscopy. FTIR-ATR (Attenuated Total Reflection) technique was used to carry out the O-ring composition analysis. Each sample O-ring was placed on the top plate of the ATR accessory and compressed by the pressure arm to ensure a good surface contact. 50 scans for each sample were applied at a resolution of 4 cm⁻¹, ranging from 4000 cm⁻¹ to 650 cm⁻¹. Spectrum of a new O-ring sample of each material was also obtained as a reference. After the acquisition of all the spectra, area changes of the representative peaks were calculated by the Spectrum One software where applicable, and multiple linear regression analysis was performed using the

PASW (formerly SPSS) software to explore the correlations between the force relaxation and peak area changes.



Figure 1. Elastocon Relaxation Tester EB 02 (source: Elastocon AB).

Fuel

A wide range of alternative fuels were tested in this study. The fuel matrix was divided into two groups, which were:

Table 1. The fuel matrix for testing.					
Rig	Fuel Matrix				
nıg —	Group 1	Group 2			
1	$FT-SPK^1 + 20\% v$	50% v BSPK ³ + 50% v			
	hexanol	Jet A-1			
2	FT-SPK + 50% v	$75\% v HVO^4 + 25\% v$			
	naphthenic	Jet A-1			
3	FT-SPK (GTL)	50% v HVO + 50% v			
		naphthenic			
4	FSJF ² (CTL)	Jet A-1			
(Ref.)					
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FT-SPK: Fischer-Tropsch Synthetic Paraffinic Kerosene

² FSJF: Fully Synthetic Jet Fuel - CTL from Sasol

³ BSPK: Bio-Derived Synthetic Paraffinic Kerosene

⁴ HVO: Hydrotreated Vegetable Oils

Group 1 This fuel matrix offers the possibility to evaluate the potential of different chemical families which are paraffinic compounds, naphthenic compounds and oxygenated compounds.

Group 2 This group compares the property of synthetic fuels produced through three pathways: HO (Hydrotreated Oils), direct liquefaction (naphthenic compounds), and BtL (Biomass to Liquid).

Sample O-Ring

Three types of O-ring materials were chosen for testing: nitrile, fluorocarbon and fluorosilicone. They were chosen not only because they represent the types of O-rings used in the current market, but also the trend of changing standard of Oring materials employed in the aviation industry. The fluorosilicone O-rings were supplied by Parker Hannifin Corporation and both nitrile and fluorocarbon O-rings were provided by Trelleborg. All O-rings have the standard AS568 113 size [22], and each type of O-rings was from the same batch to ensure the similar specification and quality. Specifications of each material are provided below.

Table 2	. Specific	ation of	sample	O-rings
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Specification	Fluorosilicone	Nitrile	Fluorocarbon
Part No.	L1218 2-113	100-113-	100-113-2326
		1109	
Color	Blue	Black	Black
ID (mm)		13.94 ± 0.18	
CS (mm)		2.62 ± 0.08	

RESULTS AND DISCUSSION

Stress Relaxation Test

When the raw data was obtained from the stress relaxation tests, F_t/F_0 was generated first to evaluate how fast each compression force relaxed with time. Then every F_t/F_0 was divided by that of the reference fuel in each group to obtain the normalized curves, comparing the relaxation characteristic with reference. The undulating shape of the relaxation curves were caused by ambient temperature fluctuation.

Nitrile

Nitrile O-rings were far more "active" than the other two materials and performed quite differently in different fuels during the relaxation process. This process could be divided into three phases (Fig. 2a):



Figure 2a. Relaxation process of nitrile O-rings: relaxation trend comparison between FSJF and Jet A-1.

Phase 1: Reduction. Force decreased sharply with time during this phase as elastomeric material is viscoelastic, which means it has both the properties of viscous and elastic materials and, as such, exhibit time dependent strain [23]. Time periods of this phase for FSJF and Jet A-1 were from the beginning to 9 h and 3 h respectively.

Phase 2: Increase. The force increase during this phase was the result of O-ring swelling caused by the aromatics in the fuels diffusing into the polymer structure [5]. The load cell of the relaxation rig sensed the pressure imposed by the volume swell of the O-ring which resulted in the increase of compression force. The relaxation curves reached a stable point at around 30 h and 40 h for FSJF and Jet A-1 respectively which also indicated the maximum volume swell points and both of them kept stable for approximately 80 hours.

Phase 3: Reduction. When the volume swell and the compression force reached an equilibrium, force began to decrease again gradually (after 110 h for FSJF and 120 h for Jet A-1) due to the fuels acting as solvents and extracting chemical components from the O-rings [5]. The difference appeared in the phase periods for FSJF and Jet A-1 might be caused by the various types of aromatic compounds in each fuel.



reference fuel (red line) in each group.

When normalized by FSJF (Fig. 2b), FT-SPK + 20% hexanol relaxed more slowly than FT-SPK + 50% naphthenic and FT-

SPK. It was noticed that because of the force increase in Jet A-1 during the process, when normalized by it, the other three fuels' performance with the nitrile O-ring was not as good as Jet A-1. All of them relaxed 15% compared with the reference after 100 hours. However, as the force in Jet A-1 finally decreased, the difference between them maintained stable and had a tendency to reduce with time. O-rings in other fuels didn't demonstrate this behavior as the aromatic content in those fuels were not high enough to cause same amount of volume change.

Fluorocarbon



Figure 3. Relaxation process of fluorocarbon O-rings, normalized by the reference fuel (red line) in each group.

Results showed that fluorocarbon O-ring has the best compatibility with all the fuels tested. Its stress relaxation characteristics in different tested fuels were quite similar to that of the reference fuel in each group; visibly overlap each other (see Fig. 3). It means fluorocarbon O-ring could probably be used in varying fuel environment as different fuel composition had little impact on its performance.

Fluorosilicone



Figure 4. Relaxation process of fluorosilicone O-rings, normalized by the reference fuel (red line) in each group.

Fluorosilicone O-ring also showed excellent compatible properties with most of the fuels except the blend of FT-SPK+ 20% hexanol in Group 1 as shown in Figure 4. It seems that the addition of 20% hexanol had accelerated the relaxation process of this elastomeric material, causing it to relax 10% more than other O-rings in this group at the end of the test.

FTIR Analysis

The purpose of FTIR-ATR technique was to identify the possible chemical structure changes that occurred during the stress relaxation test, while the O-ring materials were exposed to the test fuels. The ATR technique reflects an infrared beam from the internal surface of the crystal. It penetrates only a few microns into the sample, and structure information of the O-ring can be determined from the spectrum generated [24]. The spectra of the O-rings before and after the relaxation test are shown below.

Nitrile



Figure 5. Overall spectra of nitrile O-rings tested in Group 1 (a) and Group 2 (b) fuels.

The quality of spectra obtained for nitrile O-rings were not as good as those of fluorocarbon and fluorosilicone materials. A possible explanation was the large carbon black content in the nitrile O-rings absorbs too much IR energy, resulting in a very low transmission rate, which in return prevented a detailed spectrum analysis [25]. To improve this, the sample O-rings were sliced as thin as 10 μ m. However, even this approach did not improve the quality of spectra. Further consideration need to be taken to obtain an accurate spectrum.

Fluorocarbon

The spectra of fluorocarbon O-rings indicated that the broadest and strongest absorption occurs between 1200 and 1000 cm⁻¹, due to the C-F stretching [26]. The intensity has been increased in this region whilst decreased slightly at 2920 cm⁻¹ corresponding to C-H stretching, except for FT-SPK fuel.



Figure 6. Spectra of fluorocarbon O-rings tested in Group 1 fuels, ranging from 1450-650 cm⁻¹ (green: FT-SPK + 20% hexanol; brown: 50% FT-SPK + 50% naphthenic; red: FT-SPK; blue: FSJF; black: new O-ring).



Figure 7. Spectra of fluorocarbon O-rings tested in Group 2 fuels, ranging from 1450-650 cm⁻¹ (green: 50% BSPK + 50% Jet A-1; brown: 75% HVO + 25% Jet A-1; red: 50% HVO + 50% naphthenic; blue: Jet A-1; black; new O-ring).

To find out whether a relationship exists between the force relaxation and chemical structure changes, the PASW statistics software was used to perform data analysis. Due to the fact that it is not certain which peak area change(s) are closely related to the relaxation, a 'trial and error' method was performed. Various combinations of peak areas were evaluated to find out the most suitable variables to predict the force changes during the stress relaxation test. At last, the area changes of four representative peaks (at 1350, 1282, 1041, and 874 cm⁻¹) in the spectra were chosen. A peak area is defined as the total area between the spectrum and the zero absorbance within the range of two base points. When the two base points are set, the total

area can be calculated by the Spectrum One Software. In the first step, the Bivariate Correlation analysis was carried out to examine if there is a linear relation that directly links the force relaxation to any individual peak area changes. The results were shown in Table 3.

 Table 3. Force and spectral area changes at representative peaks of fluorocarbon O-rings.

Force	Spectral area changes $(A \cdot cm^{-1})$					
changes (N)	1350 cm ⁻¹	1282 cm ⁻¹	1041 cm ⁻¹	874 cm ⁻¹		
-22.7654	0.7936	0.5455	1.7814	2.1711		
-24.2506	0.2981	0.1446	0.8747	2.2433		
-24.0650	0.7392	0.3482	1.5908	3.3157		
-20.4904	0.2824	0.3022	0.1760	1.3692		
-20.0059	0.5716	0.2372	2.3574	3.6063		
-22.1184	0.5422	0.2076	2.0377	3.7279		
-23.9893	0.5596	0.2425	-0.7395	3.4941		
-26.1254	0.3266	0.0468	1.4079	2.5384		

 Table 4. Bivariate correlations between force changes and each peak area changes of fluorocarbon O-rings.

		Force	1350	1282	1041	874
		changes				
Force	Pearson	1	.089	.372	.204	019
changes	Correlation					
	Sig. (2-taile)		.833	.364	.628	.965
	Ν	8	8	8	8	8

It could be seen that there were no obvious correlations between the changes of force and any peak area as the Pearson Correlation coefficients were all very weak and the Significances were all much higher than 0.05. The force relaxation was not dependent on any individual chemical structure changes corresponding to these wavenumbers.

Then a Multiple Linear Regression (MLR) analysis was performed to predict the force changes using the combination of these four independent variables. This prediction model could be presented as a function:

$$y_f = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 \tag{1}$$

where y_f is the actual force changes in each tested fuel, x_{1-4} are the area changes of four chosen peaks.

Table 5. Multiple linear regression analysis of the relation between force and area changes of fluorocarbon O-rings.

Model Summary ^{a, b}							
Model R R Square Adjusted R Std. Error of the							
Square Estimate							
1	.943	.889	.741	1.04574759			
Coefficients							

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	В	Std.	Beta		
		Error			
1 Constant	-30.183	2.075		-14.544	.001
1350	-32.612	7.380	-3.121	-4.419	.022
1282	40.892	8.596	2.947	4.757	.018
1041	1.013	.433	.510	2.338	.101
874	4.333	1.102	1.797	3.931	.029
a. Dependent V b. Predictors: (C	ariable: Force Constant), 13:	e Changes (50, 1282, 1	(N) 041, 874		

The multiple correlation coefficients R and R^2 of this model were 0.943 and 0.889 which means the dependent variable and predictors are highly associated. The significance of coefficients can be further improved if bigger sample size could be analyzed as the current sample size was only eight. The prediction model could then be written as follows:

$$y_f = -30.183 - 32.612\Delta area_{1350} + 40.892\Delta area_{1282} + 1.013\Delta area_{1041} + 4.333\Delta area_{874}$$
(2)

where y_f is the predicted force changes from the model. When the values of variables were substituted into the equation, a set of y_f were obtained and plotted against y_f . The predicted and actual force changes fitted very well as can be seen from Figure 8. This demonstrates that the model represents a linear relationship between the force changes and the combination of all four peak area changes. In another word, the peak area changes at specific wavenumbers could determine the force relaxation of a fluorocarbon O-ring.



Figure 8. Plot of predicted force changes against actual force changes for fluorocarbon O-rings.

Fluorosilicone



Figure 9. Overall spectra of fluorosilicone O-rings tested in Group 1 fuels (blue: FT-SPK; brown: 50% FT-SPK + 50% naphthenic; red: FSJF; green: FT-SPK +20% hexanol; black; new O-ring).



Figure 10. Overall spectra of fluorosilicone O-rings tested in Group 2 fuels (blue: 50% BSPK + 50% Jet A-1; brown: 75% HVO + 25% Jet A-1; red: 50% HVO + 50% naphthenic; green: Jet A-1; black: new O-ring).

The spectra of fluorosilicone O-rings in Figure 9 and 10 showed the strongest band at 1000 cm⁻¹, which is caused by the vibration of C-F stretching. It could be seen that the intensity of the band near 1060 cm⁻¹, which is corresponding to the (Si-O-Si) stretching, decreased sharply after the relaxation test. Similar observations can be made for the characteristic bands at 1270 cm⁻¹ cause by (Si-CH₃) bending; and at 1210cm⁻¹ because of C-F stretching [26].

By contrast, absorption at around 3680 cm⁻¹, as well as the region from 3000 to 2800 cm⁻¹, increased. The characteristic band at 3680 cm⁻¹ is due to the O-H stretching, and C-H stretching is the mode for the bands from 3000 to 2800 cm⁻¹.

From the observed phenomena, it is suggested that all the fuels tested might chemically impact the molecular structure of fluorosilicone O-rings. The reduction of intensity in certain regions of the spectra may indicate the breakdown of corresponding structures, while the increase of absorption may be the result of gaining certain chemical bonds. Although a fluorosilicone O-ring as a polymer consists of macromolecules, its characteristic large size has little effect on its chemical properties. This means the functional groups in the molecule determine the kind of chemical reactions that would possibly occur [27]. Then, the key to understand the chemical reasons for fuel impact on fluorosilicone O-rings lies in investigating the potential chemical reactions which would occur amongst these functional groups. A typical molecular structure of fluorosilicone elastomer containing trifluoropropyl methyl siloxane units [28] is shown below:



Figure 11. The chemical structure of fluorosilicone [29].

As the strongest single bond in organic chemistry, C-F bond tend to be chemically inert and stable. The bond also strengthens as more fluorines are added to the same carbon on a chemical compound [30]. The highest peak caused by C-F stretching at 1000 cm⁻¹ in Figure 9 and 10 didn't change much which also proved its stability. Conversely, the most notable break down occurred to the (Si-O-Si) bond, as the absorption at 1060 cm⁻¹ dropped dramatically. Results from the stress relaxation tests indicate a relatively incompatible performance of fluorosilicone O-ring in FT-SPK+20% hexanol. A possible explanation for this is that when the (Si-O-Si) bonds broke down, the –OH group in hexanol replaced the position of oxygen and formed a new (Si-OH) bond with silicone. This resulted in the reduction of absorption intensity of (Si-O-Si) bonds and the increase of O-H bonds in the final spectra.

The same statistics analysis procedure used in analyzing fluorocarbon O-rings was carried out here to investigate the fluorosilicone O-rings. The independent variables chosen were the peak area changes at 1263, 1060, 764, and 669 cm⁻¹ respectively. Results for both Bivariate Correlations and MLR analysis were summarized below.

	nuo		ng5.				
Force	orce Spectral area changes $(A \cdot cm^{-1})$						
changes (N)	1263 cm ⁻¹	1060 cm ⁻¹	764 cm ⁻¹	669 cm ⁻¹			
-47.6211	-1.1440	-10.0686	-4.0950	-0.0242			
-44.7071	-1.6130	-17.3576	-8.9251	0.9435			
-41.5847	-1.6824	-17.431	-6.1885	0.6437			
-61.5866	-1.5968	-22.6178	-8.0815	2.2444			
-39.3772	-1.6250	-21.3593	-9.8643	1.6357			
-39.0432	-1.2441	-21.2303	-7.3842	2.0032			
-36.6286	-1.7443	-20.0795	-6.9175	1.1496			
-42.5893	-1.3216	-21.1844	-9.4867	2.1067			

 Table 6. Force and spectral area changes at representative peaks of fluorosilicone O-rings.

 Table 7. Bivariate correlations between force changes and each peak area changes of fluorosilicone O-rings.

		Force	1263	1060	764	669
		changes				
Force changes	Pearson Correlation	1	065	.005	066	183
	Sig. (2-taile)		.879	.992	.876	.664
	Ν	8	8	8	8	8

 Table 8. Multiple linear regression analysis of the relation between force and area changes of fluorosilicone O-rings.

Model Summary ^{a, b}							
Model	R	R R Square		Adjusted R	Std. Error	• of the	
				Square	Estim	ate	
1	.943	.88	9	.742	3.9864	358	
			Coeffic	cients			
Model	L	Instand	ardized	Standardi	t	Sig.	
		Coeffic	cients	zed			
				Coefficien			
				ts			
		В	Std.	Beta			
			Error				
1 Constant	-10	2.954	18.055	5	-5.702	.011	
1263	321	2.782	872.65	2 3.763	3.682	.035	
1060	-65	8.317	173.89	6 -7.133	-3.786	.032	
764	-71	4.089	299.65	3 -2.533	-2.383	.097	
669	-107	6.619	234.30	4 -6.842	-4.595	.019	
a. Dependent	Variable	: Force (Changes (N	A)			
b. Predictors:	(Constai	nt), 1263	, 1060, 764	4, 669			

The value of R^2 was 0.889 which also indicated this is a good model to predict force changes via the four predictors. The prediction model could be presented when substituted all the coefficients into the formula:

$$y_{f} = -102.954 + 3212.782\Delta area_{1263} - 658.317\Delta area_{1060} - 714.089\Delta area_{764} - 1076.619\Delta area_{669}$$
(3)

where y_f is the predicted force changes from the model. When the predicted force changes were plotted against the actual force changes, it also presented a well fitted linear relationship, which means this model is also applicable to fluorosilicone O-rings.



Figure 12. Plot of predicted force changes against actual force changes for fluorosilicone O-rings.

It is interesting to notice that although none of the individual peak area changes showed linear relationship with the force changes, the combination of them were highly correlated with the force relaxation. This could possibly indicate that the force relaxation of an O-ring is not determined by any single chemical structure change but is dependent on the combined impact of all the structure changes. Amongst these chemical structures, however, some particular changes may be more influential than others. For instance, the area changes at 1350 and 1282 cm⁻¹ might be more influential on fluorocarbon Orings' performance than those at 1041 and 874 cm⁻¹, as their weights in the model equation are much bigger than the others'. More tests are needed to gain more reliability in these results. Once certain chemical components which have negative influence on the performance of particular O-ring material could be identified, efforts can be made to eliminate or substitute these components during the material manufacturing process.

CONCLUSIONS

Fluorocarbon O-rings showed the best compatibility with all the alternative fuels tested in the stress relaxation tests amongst the three O-ring materials. Little physical or chemical changes were observed, indicating its excellent stability. Fluorosilicone O-rings were also compatible with all of the fuels tested with the exception of hexanol. Due to the significant changes in the fluorosilicone O-rings when used with hexanol, concern should be raised when using it in an environment containing alcohols. Nitrile O-rings seem to be more easily affected by the composition changes of fuels, especially the aromatic content of the fuels. Changes of certain chemical structures in an O-ring have a combined linear impact on its stress relaxation process. Particular structure changes might be more influential than others depending on the different materials of the O-rings.

The combination of stress relaxation tests and FTIR analysis techniques provided a powerful approach in investigating elastomer compatibility with potential aviation fuels. The chemical specificity offered by FTIR enables the sealing performance of an O-ring to be correlated to molecular level information, which could present the in-depth reasons for the behavior of sealing components.

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