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Testing the Effects of a Bio-Derived Alternative Aviation Gasoline on Aircraft Materials In
Comparison to 100 Low Lead Aviation Gasoline

Submitted to the Faculty of Purdue University, in Partial Fulfillment of the Requirements for the
Master of Science degree in Aviation and Aerospace Management

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Abstract

Within the past decades, there has been increasing interest in alternative fuels in the aviation industry. However for these alternative fuels to be accepted they must show they do not affect materials, particularly elastomers, in aircraft significantly different than standard 100 low lead (100LL). This research is focused on comparing the effects of a proprietary bio-derived alternative fuel on elastomers against 100LL. Materials to be tested are Buna-N vinyl, neoprene, nitrile, plain cork, neoprene and cork (backed cork), Viton, high-purity silicone, polyester, polysulfide and rubber hose. The testing to be performed includes volume swell, tensile strength, elongation, durometer hardness and density. The samples were soaked in fuel for a period of 28 days at room temperature, 71°C and 93°C. All testing will be done in accordance with respective ASTM standards. Due to proprietary concerns, actual measurement cannot be reported, but differences between the two fuels can, i.e. the percentage difference between materials soaked in 100LL and the bio-derived alternative. Statistical methods were applied to the volume change, tensile strength and elongation tests to determine significant differences. The largest difference in volume swell was for backed cork, the largest difference in tensile and elongation was in neoprene, the largest difference in density was in nitrile, and plain cork exhibited the largest difference in durometer hardness. Viton and polyester exhibited no significant differences. Limited testing conducted with a second bio-derived alternative showed polysulfide as having the greatest difference between the two bio-derived fuels.

Introduction

In recent years the aviation industry has become increasingly interested in finding an alternative fuel source to petroleum-based fuels. Many have seen the potential market in developing a new alternative fuel source, and as a result there have been numerous potential

alternative fuel sources identified. One such fuel stream that has received attention is that of biofuel. This research is focused particularly on a specific bio-derived fuel, which due to its proprietary nature, will be referred to throughout this paper as the test fuel. The goal of this research is to determine if this test fuel has a significant effect on aircraft materials when compared to 100 low lead aviation gasoline (100LL or 100 LL), and if there is a significant difference, to report what that difference may be. However, due again to proprietary concerns, the actual measurements and data obtained from this research cannot be reported, but it is possible to report the magnitude of the difference if such results occur. These findings will be given as a percentage of differences between materials soaked in the separate fuels.

Literature Review

Over the past few decades there has been increasing interest in finding an alternative fuel source to the standard petroleum fuel source that is used today. This interest has been generated globally, in all markets and industries. Any industry that requires the use of a petroleum-based fuel, diesel, kerosene, jet fuel, or gasoline, has begun to look at alternative fuels to reduce costs as well as to become more environmentally conscious and develop secure sources. Aviation is one such industry, including, commercial, military and general aviation sectors.

For an alternative fuel to be successful, it needs to be able to operate within the same parameters as that of the petroleum fuel that it is replacing without degrading performance in an appreciable manner. Essentially, the alternative fuel must have the same BTU content and produce the same amount of thrust or power. Moses and Roets (2009) successfully demonstrated a fully synthetic jet fuel that performed similarly to a standard petroleum jet fuel. The jet fuel that the authors researched went on to become the first ever certified fully synthetic jet fuel under DEF STAN 91-91 of the United Kingdom (UK) Aviation Fuels Committee. ASTM International

has also been researching the use and certification of alternative aviation fuels, particularly jet fuel. In 2011, ASTM D7566 – 11a became the official standard by which alternative jet fuel was to be developed and tested. This standard allows a synthesized hydrocarbon to be blended with standard Jet-A and, to the extent that it can be shown that such blends do not perform significantly different than standard Jet-A, may be approved for use under ASTM D1655-12, the standard for Jet-A. In technical report DOT/FAA/AR-06/43 released by the Federal Aviation Administration (FAA) it was reported that a blend of 85% ethanol, 14% pentane isomerate, and 1% biodiesel, termed Aviation grade ethanol (AGE85), performed in similar fashion to the standard 100 LL used in general aviation, although AGE85 required 57% more fuel mass flow or 35% more fuel flow volume. The engine used in the research was a Lycoming IO360-C model engine and only required minor modifications, retarding timing by 5° and a change in fuel scheduling (FAA, 2006).

Engine performance characteristics are not the only properties that must be considered when developing and evaluating alternative fuels. The interactions between the fuel and the materials that the fuel will come into contact with are also very important. Fuel systems contain both metallic and elastomer components, and these can react very differently when in contact with fuel. While it has been shown that certain metals can react negatively or corrode when they come into contact with ethanol-based fuels (Hansen, Zhang & Lyne, 2005), the reactions of elastomers with these new alternative fuels is of particular interest (Flitney, 2007). Thomas (2009) studied the effects of different blends of ethanol and butanol on several different compositions of fluoroelastomers, or Viton®. The samples of Viton® were soaked in the differing fuel blends at 40°C for 1000 hours in accordance with ASTM D 471-98. This research found that when evaluating the samples of Viton® for hardness with a durometer in accordance with ASTM

D 2240-02, all compositions softened when exposed to a bio-alcohol fuel. The largest amount of softening occurred when Viton® was exposed to fuel blends that contained both ethanol and a fuel with high aromatic content. This research also discovered that there was a loss of tensile strength, evaluated in accordance with ASTM D 412-98a using Die C, when exposed to the fuel blends, and again the greatest degree of tensile loss came when the samples were exposed to blends with both ethanol and a high aromatic content. Volume swell was also evaluated in the course of the research. As the previous results have shown, the largest amount of swelling occurred in those samples that were exposed to fuel blends of ethanol and high aromatics. One interesting result was that samples soaked in 100% butanol exhibited the least of amount of swell.

Research conducted by Jones, Mead and Steevens (2008) tested the effects of two different ethanol blends, E10 (10% ethanol/90% ASTM Fuel C) and E20 (20% ethanol/80% ASTM Fuel C), on eight different plastic materials: acrylonitrile butadiene styrene (ABS), polyamide 6 (PA 6) [Nylon 6], polyamide 66 (PA 66) [Nylon 66], polybutylene terephthalate (PBT), polyethylene terephthalate (PET), polyetherimide 1010 moldable (PEI), polyurethane 55D-90(PUR) and polyvinyl chloride flexible version (PVC). The research showed that for PA 6, PA 66, PBT, PET, and PEI volume changed approximately 10% when exposed to the fuel blends. PUR swelled by 54.7% in E10 and over 60% in E20, and PVC shrunk by 35%. The tensile strength of the PA 6, PA 66, PBT, PET, and PEI all decreased when exposed to the fuel blends, but with no significant difference between the two blends. PUR samples lost 73% of their strength in E10, but the samples in E20 broke before they were able to be tested.

Material compatibility with a soy biodiesel has also been studied extensively (Haseeb, Jun, Fazal & Masjuki, 2010; Trakarnprunk & Porntangjitlikit, 2008). Trakarnprunk and

Porntangjitlikit (2008) created their own biodiesel using transesterification and then blended with diesel in a 10% bio/90% regular diesel blend. The materials tested in the blend of biodiesel were nitrile rubber (NBR), hydrogenated nitrile rubber (HNBR), nitrile-PVC blend (NBR/PVC), acrylic rubber, co-polymer FKM (Viton®), and terpolymer FKM (Viton®). The samples were soaked in the biodiesel blend at 100°C for periods of 23, 670, and 1008 hours, in accordance with ASTM International standards. The test performed at each interval were volume change (swell), tensile strength, and hardness, all performed in accordance with ASTM International Standards. Acrylic rubber showed the largest amount of swell followed by HNBR and the two Viton® samples. Both NBR and NBR/PVC showed negative swelling, or shrinking, when exposed to biodiesel. All samples except NBR and NBR/PVC softened when exposed to the biodiesel. The research also showed that for all samples, except HNBR, tensile strength decreased, although not significantly.

The research conducted by Haseeb et al. (2011), while similar to that of Trakarnprunk and Porntangjitlikit (2008) differed by testing different materials (ethylene propylene diene monomer (EPDM), silicone rubber (SR), polychloroprene (CR), polytetrafluoroethylene (PTFE) and nitrile rubber (NBR)) and using different ratios of fuel blends of diesel and palm biodiesel. The soak time, 1000 hours, and temperature, 25°C, differed from earlier experiments as well. For volume swell the research showed that CR and NBR swelled when exposed to biodiesel blends, which is the opposite result found by Trakarnprunk et al., and that EPDM and SR swelled when exposed to regular diesel. It was also found that PTFE shrank when exposed to biodiesel. EPDM, CR and NBR experienced more degradation of tensile strength and loss of hardness than did CR or SR. Also, Frame and McCormick (2005) found that NBR tends to swell, rather than shrink,

when exposed to biodiesel which agrees with by Haseeb et al. (2011), and again contradicts Trakarnprunk and Porntangjitlikit (2008).

There has been exhaustive research conducted on the materials compatibility of alternative fuels, and research is in fact still progressing. As new alternative fuels are developed they need to be tested because each new fuel source is unique, with specific chemical compositions. In fact, even fuels that have the same source can perform vastly different, i.e, the results of Trakarnprunk and Porntangjitlikit (2008) versus Haseeb et al. (2011) and Frame and McCormick (2005). This could be attributed to either the variations in the batches of the samples or the unique way the fuel was prepared, perhaps as a result of differences between lab methods and industrial production practices.

It is worth mentioning that there exists no clearly defined standard for materials compatibility testing in either the materials to be tested or qualitative standards to assess performance. Every researcher chose a different set of materials to be tested, most likely based on ease of use, availability, previous experience or a combination of the three. Of course there were certain materials that were regularly used, because of the commonality of industry usage, but a defined standard may allow more accurate, consistent, and meaningful results. The second point, a qualitative standard, would also allow for more meaningful results. If a standard set of materials is used, a qualitative standard can be established to determine whether a material performs satisfactorily or fails to meet standards. Not only would this allow meaningful comparable results, but the end user of both the fuel and the material could be assured that their equipment will work safely and properly.

Proposed Methodology

Materials to be evaluated for compatibility with the test fuel are representative of materials found in aircraft, not just materials that are most likely to come into contact with fuel, which include but are not limited to: various sealant materials, hosing and tubing material. The tests performed were: volume swell, tensile strength, elongation, durometer hardness and density. The samples were tested in four different fuel blends, two test fuels and two 100LL baselines, and were tested using three different temperatures ranges: room temperature (baseline), 71°C and 93°C. Appendix A provides a comprehensive list of the materials to be tested and corresponding tests to be performed on the material.

Volume Swell

Three samples from every material were cut for each fuel to be tested. These samples were cut into rectangular pieces measuring approximately 25.4mm by 50.8mm (1.00in by 2.00in). The exact length and width of the samples were then measured with a caliper and the thickness was measured with a micrometer and the measurements were recorded. After the fuel soak period elapsed the samples were again measured (length, width and thickness) and the data was recorded. The volumes of the samples before and after exposure to the fuel were obtained from the measurements taken and the percentage change in volume was calculated using the following formula:

$$\frac{\text{Volume}_{\text{exposed}} - \text{Volume}_{\text{original}}}{\text{Volume}_{\text{original}}} \times 100\%$$

Tensile and Elongation

For tensile and elongation testing three dumbbell shaped samples were cut from every material for each fuel to be tested. The dumbbell pieces were cut using an ASTM D412-06a standard Die C, and a 3-ton press. After the samples have been exposed to the fuel, an Instron®

model 1130 stress and strain instrument, with a 100 pound load cell and crosshead speed of 10 inches per minute, was used to pull the samples. The samples were then pulled until failure and the distance traveled by the grips and the force required were recorded. To determine elongation the grips of the instrument will be set apart by a fixed distance (gage length) of 3.5 inches.

Elongation will be calculated using the following formula:

$$\frac{Distance - Gage Length}{Gage Length} \times 100$$

For tensile strength the original cross sectional area of the narrow part of the dogbone will be recorded as well as the change in volume. Tensile strength was calculated with the following formula:

$$Force / Original Area \times (1 + \Delta Vol / 100)^{2/3}$$

Durometer

Durometer readings, a measure of hardness, were taken using a manual Instron Shore A durometer (hardness tester). In order to obtain accurate readings the samples to be measured must be at least 6 mm thick, which required most samples to be stacked together in order to obtain the minimum thickness. For samples that were too thin or cumbersome to stack to minimum thickness, the samples were placed on top of the calibration block provided with the durometer.

Density

To obtain density, two different methods were used. For samples that sank in water (density greater than 1.00 g/cc) a Jolie balance with a density kit was used. For samples that floated in water (density less than 1.00 g/cc) density was determined by dividing the mass of the sample in air by the volume of the sample.

Fuel Soak

After the samples were prepared they were soaked in fuel at the proper temperature. The proper temperature was determined by examining both the operating specifications and common operating temperatures of the materials and testing at the higher of the two temperatures. The samples were placed in either a 1 pint or 1 quart Mason jar. Spiral safety wire racks were used to arrange samples in a way to facilitate maximum exposure to the fuel. After the samples were placed and arranged properly, fuel was added to a level that provided total immersion and the fuel soak test began. The samples soaked at the elevated temperatures were placed in a Stabil-Therm constant temperature cabinet at the proper temperature. The samples tested at room temperature were placed in a flammables cabinet. The samples were soaked in fuel for a total of 28 days, with the fuel being changed at the halfway point at 14 days.

After the measurements were taken, statistical methods were applied to determine if there was a significant difference between the effects of the bio-derived gasoline and 100 LL. Due to the fact that no standards exist on how bio-derived fuels should affect aircraft materials, a qualitative assessment cannot be given. Also, as mentioned above, due to the proprietary nature of the fuel the hard data cannot be reported, but an assessment of the magnitude of difference can be stated, more simply put a percentage in the difference between the test fuel and 100 LL measurements will be reported. All testing and measurements were done in accordance with the following ASTM Standards: ASTM D412-06a Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers-Tension, ASTM D2240-05(2010) Standard Test Method for Rubber Property—Durometer Hardness, ASTM D471-06 Standard Test Method for Rubber Property-Effect of Liquids, ASTM D792-08 Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement.

Results

Appendix B shows the full list of test results. The numbers displayed in the cells indicate percentage change from original or baseline measurements. For example, Buna soaked in 100 LL changed in volume by an average of 12 percent, where Buna soaked in test fuel one (Bio 1) changed in volume by an average of 44 percent. The p value column shows the p value of a two sample T-test assuming unequal variances, with a hypothesized difference of 0 and an alpha value of 0.05, with sample sizes ranging from 2 to 9. A positive value in the volume column indicates swelling and negative indicates shrinking. For tensile strength a positive value represents an increase in strength whereas negative indicates a weakening effect. Positive elongation values indicate the material stretched more, with a negative showing a decrease in stretch before failure.

T-tests were used only on volume, tensile, and elongation due to those tests having the greatest data available. Because durometer readings required the samples to be stacked together, as described above, there was only one data point for approximately every three samples. Density was determined, for a majority of samples, by measuring the density of a small piece removed from the samples and using that reading as the density of all pieces.

Through the course of testing, the manufacturer of the bio-derived alternative identified the original sample of fuel that was used in testing had been contaminated and was not representative of the fuel that would be produced from full-scale manufacturing process. So a new sample of fuel was delivered that would more closely represent the final full-scale manufactured product (Bio 2), and a few materials were selected to re-test. Table 2 shows the materials and results.

| Material | Temperature | Volume | | | Tensile | | | Elongation | | | Durometer | | Density | |
|---------------|--------------------------------|--------|-------|---------|---------|-------|---------|------------|-------|---------|-----------|-------|---------|-------|
| | | AvGas | Bio 2 | P Value | AvGas | Bio 2 | P Value | AvGas | Bio 2 | P Value | AvGas | Bio 2 | AvGas | Bio 2 |
| Buna | Rm Tmp | 12 | 43 | 0.0133 | -72 | -81 | 0.1444 | -25 | -48 | 0.0178 | -17 | -37 | -6 | -11 |
| Buna | 71°C | 11 | 36 | 0.0000 | (1) | (1) | (1) | (1) | (1) | (1) | -19 | -27 | 3 | -15 |
| Neoprene | Rm Tmp | 13 | 65 | 0.0286 | -2 | -46 | 0.0003 | -11 | -32 | 0.0567 | -14 | -31 | -5 | -12 |
| Nitrile | 93°C | -19 | 6 | 0.0000 | -59 | -75 | 0.0082 | -82 | -42 | 0.0004 | 2 | -75 | 130 | 319 |
| Polysulfide 2 | 93°C | -9 | 11 | 0.0062 | -78 | -68 | 0.1532 | -74 | -44 | 0.0533 | -20 | -40 | -1 | -9 |
| (1) | Tensile tester was inoperative | | | | | | | | | | | | | |
| (2) | Test not performed | | | | | | | | | | | | | |
| (3) | Samples to degraded to test | | | | | | | | | | | | | |

Table 2

Discussion

As can be seen in the table of results in Appendix B the only materials with no significant difference between Bio 1 and 100 LL were polyester and Viton. In the case of polyester only the volume test was performed because the material was so hard that cutting and testing a sample of the material for tensile and elongation was not possible with the equipment available. Given equipment with the necessary capabilities, it would be possible to test for tensile and elongation. With Viton, tests were only conducted at room temperature so it is possible that a difference would be exhibited if testing was conducted at an elevated temperature.

The largest difference in volume change was exhibited by backed corked due to the porosity of the cork. The largest total volume change occurred in the high purity silicone samples. Neoprene exhibited the most difference between 100 LL and Bio 1 in both tensile strength and elongation. Plain cork exhibited the largest difference in durometer hardness, and the biggest difference in density was shown by nitrile. When the select samples were retested with Bio 2 polysulfide shown the most difference between the two test fuels, with each significance test changing from significant to insignificant and vice-versa.

One interesting observation was that both types of cork did not react well with Bio 1. In the case of plain cork, the samples soaked in Bio 1 at 71 degrees completely disintegrated and only small chunks of the samples were left in the bottom of the jar. While backed cork did not

completely disintegrate, for both elevated temperatures when soaked in Bio 1 the samples were too degraded to test. If they did not fall apart while being removed from jars or while being handled, they would instantly break in the grips of the stress and strain machine when a load was applied.

A couple of problems arose during the course of testing. First, the original samples of polysulfide were determined by the manufacturer to be slightly contaminated and new samples were sent. Further testing was conducted to determine if any significant difference existed, and only the tensile strength for 100 LL and volume swell for Bio 1 were found to be different. Second, after the fuel soak at 71 degrees centigrade was conducted it was found the stress and strain instrument was not functioning properly and a backup instrument could not be found in the proper timeframe. As a result, tensile and elongation tests could not be performed for the 71 degree fuel soak.

Conclusion

This research shows that for a majority of the materials tested, with only two exceptions, the test fuel has a significantly different effect than 100 LL on at least one characteristic (volume, tensile, or elongation). However in the case of the two materials not tested, it is possible that further testing with the correct equipment may find significant differences. It is also very likely that with more powerful T-tests, i.e. larger sample sizes, more significant differences would be found, and, in fact, more testing is currently being conducted to gather more data and provide larger sample sizes. It would also be beneficial to run full tests on all sample materials with Bio 2 to better understand how the full-scale production bio-alternative will affect the materials.

Research in this area would also be aided by having set testing standards dedicated to alternative fuels research. While the standards that exist now, namely ASTM standards, are serviceable, they are mainly focused on the testing of current petroleum distillates and as evidenced by this research, alternative fuels may affect materials differently, therefore testing and handling standards may need to be revised. Qualitative standards are another matter. Currently there exists no standard to determine what is an acceptable volume swell, tensile strength, elongation, etc., of a material soaked in fuel. When these tests are conducted the data is simply reported, and there is no pass/fail or good/bad. With new fuels being developed that affect current materials differently, it may be pertinent to define a standard by which the new fuel can be considered acceptable for use.

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Appendix A

| | Dimensional | Tensile | Elongation | Durometer | Density | Adhesive Lap Shear | Room Temperature | 71°C | 93°C |
|-----------------------------|-------------|---------|------------|-----------|---------|--------------------|------------------|------|------|
| Buna Vinyl | X | X | X | X | X | | X | X | |
| Cork - Plain | X | X | X | X | X | | X | X | |
| Cork - Coated | X | X | X | X | X | | X | X | X |
| Nitrile | X | X | X | X | X | | X | | X |
| Polysulfide | X | X | X | X | X | | X | | X |
| Viton | X | X | X | X | X | | X | | |
| Polyester | X | X | X | X | X | | X | X | |
| High Purity Silicone | X | X | X | X | X | | X | | |
| Neoprene | X | X | X | X | X | | X | | |
| Rubber Hose | X | | | X | X | | X | X | |

BIO-DERIVED FUEL EFF

| Material | Temperature | Volume | | | Tensile | | | Elongation | | | Durometer | | | Density | |
|---------------|--------------------------------|--------|--------|---------|---------|--------|---------|------------|--------|---------|-----------|--------|--------|---------|-------|
| | | AvGas | Bio 1 | P Value | AvGas | Bio 1 | P Value | AvGas | Bio 1 | P Value | AvGas | Bio 1 | AvGas | Bio 1 | AvGas |
| Buna | Rm Tmp | 12 | 44 | 0.0060 | -72 | -78 | 0.3044 | -25 | -57 | 0.0000 | -17 | -34 | -6 | -14 | |
| Buna | 71°C | 11 | 63 | 0.0038 | (1) | (1) | (1) | (1) | (1) | (1) | (1) | (1) | (1) | (1) | |
| Polyester | Rm Tmp | 2 | 0 | 0.3655 | (2) | (2) | (2) | (2) | (2) | (2) | (2) | (2) | (2) | (2) | |
| Polyester | 71°C | 2 | 2 | 0.8694 | (1)(2) | (1)(2) | (1)(2) | (1)(2) | (1)(2) | (1)(2) | (1)(2) | (1)(2) | (1)(2) | (1)(2) | |
| Viton | Rm Tmp | 4 | 7 | 0.3724 | 1 | 0 | 0.7604 | 9 | 12 | 0.6532 | -6 | -7 | -5 | -5 | |
| Silicon | Rm Tmp | 116 | 150 | 0.0183 | -59 | -77 | 0.0038 | -46 | -66 | 0.3163 | -36 | -35 | -26 | -18 | |
| Plain Cork | Rm Tmp | 10 | 12 | 0.4822 | -37 | -50 | 0.3680 | -27 | -50 | 0.0362 | 137 | 297 | 6 | 11 | |
| Plain Cork | 71°C | 4 | (1)(3) | -- | (1) | (1)(3) | -- | (1) | (1)(3) | -- | 4 | (1)(3) | 236 | (1)(3) | |
| Backed Cork | Rm Tmp | 22 | 66 | 0.0000 | -91 | -73 | 0.0508 | -29 | -23 | 0.7117 | 21 | 21 | 21 | 21 | |
| Backed Cork | 71°C | 54 | 160 | 0.0000 | (1) | (1) | (1) | (1) | (1) | (1) | 13 | -64 | 21 | 22 | |
| Backed Cork | 93°C | 32 | 121 | 0.0000 | (3) | (3) | (3) | (3) | (3) | (3) | 22 | 20 | 22 | 20 | |
| Rubber Hose | Rm Tmp | 18 | 51 | 0.0120 | (2) | (2) | (2) | (2) | (2) | (2) | -14 | -25 | -6 | -21 | |
| Rubber Hose | 93°C | 17 | 64 | 0.0078 | (2) | (2) | (2) | (2) | (2) | (2) | -40 | -62 | -5 | -18 | |
| Neoprene | Rm Tmp | 13 | 60 | 0.0315 | -2 | -79 | 0.0000 | -11 | -60 | 0.0000 | -14 | -36 | -5 | -14 | |
| Nitrile | Rm Tmp | 6 | 23 | 0.0055 | -38 | -65 | 0.0016 | 7 | -12 | 0.0033 | -12 | -59 | 41 | 19 | |
| Nitrile | 93°C | -19 | 22 | 0.0014 | -59 | -74 | 0.0229 | -82 | -61 | 0.0020 | 2 | -37 | 130 | 30 | |
| Polysulfide 1 | Rm Tmp | 7 | 12 | 0.1418 | -12 | -22 | 0.1444 | -3 | 24 | 0.0042 | 18 | -11 | 16 | -5 | |
| Polysulfide 1 | 93°C | -4 | 26 | 0.0689 | -91 | (2) | -- | -77 | (2) | -- | -22 | -83 | -1 | -11 | |
| Polysulfide 2 | Rm Tmp | -1 | 20 | 0.0073 | (1) | (1) | (1) | (1) | (1) | (1) | 22 | -38 | -1 | -11 | |
| Polysulfide 2 | 93°C | -9 | -11 | 0.5103 | -78 | -97 | 0.0274 | -74 | -86 | 0.1136 | -20 | -76 | -1 | -11 | |
| (1) | Tensile tester was inoperative | | | | | | | | | | | | | | |
| (2) | Test not performed | | | | | | | | | | | | | | |
| (3) | Samples to degraded to test | | | | | | | | | | | | | | |