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Thermal Aging of the Polyurethane Foam for the H1259 Storage Container

Roger A. Assink, Mathias C. Celina, and Julie M. Elliott

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Roger A. Assink, Mathias C. Celina, Julie M. Elliott
Organic Materials Dept. 1821

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1411

Abstract

A polyurethane foam bottom cushion, part number 272011, of the H1259 storage container is used to shield the container's contents from shock and vibration. The specifications for the force at 50% compression are stated to be 4.5 to 7.5 psi. We have performed extensive tests of compressive force as a function of time at elevated temperatures and used this information to derive acceleration factors for aging of this foam from 80 to 140°C. However, considerable uncertainty is introduced if these acceleration factors are extrapolated in order to calculate service lifetimes at ambient conditions. Chemical detection methods are often more sensitive than the mechanical methods used to monitor the aging process. The temperature dependence of the chemical process can then be applied to the mechanical measurement in order to predict the service life of the material. We have adapted a commercial respirometer, used for measuring respiration of small biological organisms, to measure the extremely low oxidation rates of the polyurethane foam. Polyurethane samples were placed in a sealed chamber, filled with air and allowed to oxidize at a fixed temperature for a period of time. At the end of the oxidation period the oxygen depletion of the sample chamber was measured by the respirometer. The oxidation rates of the polyurethane foam were measured from 23 to 110°C and acceleration factors over this temperature range calculated. The oxidation acceleration factors measured by the respirometer were compared to those measured for the compressive strength of the foam at elevated temperatures and then used to predict acceleration factors and service life for the compressive strength of the foam under ambient conditions. Adding fire retardant to the polyurethane formulation reduces the oxidation rate of the foam.

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Nomenclature and Abbreviations

PU = polyurethane
 UOC = Ultrasensitive oxygen consumption

1. Introduction

The polyurethane bottom cushion, part number 272011, of the H1259 storage container is used to shield the container's contents from shock and vibration. The specifications for compressive force at 50% are stated to be 4.5 to 7.5 psi. We have performed extensive tests of compressive force as a function of time at temperatures ranging from 80 to 140°C. These tests were used to derive acceleration factors for aging (relative speed of degradation) of this foam. Considerable uncertainty is introduced, however, if these acceleration factors are extrapolated from elevated temperatures to ambient conditions in order to calculate service lifetimes. We are also investigating the chemical changes associated with polymer aging [1,2]. In addition to providing insight into the aging mechanism, it is often possible to measure chemical changes associated with aging with more sensitivity than mechanical changes associated with aging. This increased sensitivity can be used to measure the very low rate of degradation at ambient conditions, so that extrapolation from high temperature behavior to low temperature behavior can be made in a scientific manner.

Oxidative processes are the primary degradation mechanisms for many polymers exposed to ambient environmental conditions. The report by Scheirs *et al* [3] provides an excellent review of the various methods of oxygen uptake used to measure polymer oxidation rates. A majority of the more than 100 studies summarized in the review calculate polymer oxidation rates from the time dependence of the head gas pressure in a closed aging vial, which is measured by either a manometer or pressure transducer [4]. Pressure measurements can be complicated by contributions from gaseous oxidation products, such as water and CO₂, which are therefore often removed by molecular sieves and adsorbents. Other investigators have used gravimetric methods [5] and electrode sensors [6,7] to measure oxidation rates. Gas chromatographic (GC) techniques have been employed to measure oxygen partial pressures [8] and notably can independently measure the contributions from both the oxygen and gaseous oxidation products. Wise *et al.* further developed the GC approach into the ultrasensitive oxygen consumption (UOC) method which provides a powerful tool for predicting acceleration factors over a wide temperature range, including ambient temperature, and for understanding fundamental phenomena of oxidative polymer degradation [9,10]. This method enables degradation rates for mechanical properties measured at elevated temperatures to be more accurately extrapolated to ambient temperatures [11]. In the UOC experiment, a polymer sample is placed into an ampoule containing a known pressure and volume of oxygen. After an aging period at a fixed temperature, the gas composition in the free volume is analyzed by a GC technique and the total amount of oxygen consumed is determined. The UOC method has been used extensively to predict the lifetime of polymers undergoing thermo-oxidative aging [11-15].

In this report we describe the use of a commercial differential fuel cell respirometer to measure oxidation rates of polymeric materials. This instrument has been successfully employed for measuring the respiratory cycles of small animals and insects in real time [16,17]. We have adapted the operation of the instrument for measuring the extremely low oxidation rates of polymers [18]. Polymer samples were placed in a sealed chamber, filled with air and allowed to oxidize at a fixed temperature for an extended period of time. At the end of the oxidation period the sample chamber was flushed with a flow of air and the oxygen depletion measured by the respirometer. Experiments on bulk natural rubber were used to confirm that these measurements were in agreement with UOC measurements. The oxidation rates of the 0.1 g/cm³ polyurethane foam were measured from 23 to 110°C and acceleration factors over this temperature range calculated. The oxidation acceleration factors measured by the respirometer were compared to those measured for the compressive strength of the foam at elevated temperatures and then used to predict acceleration factors and service life for the compressive strength of the foam under ambient conditions. The oxidation rates of a polyurethane foam with a fire retardant additive was also measured.

2. Experimental

Materials. The polyurethane foam for the H1259 storage container is a flexible, open-celled foam with a density of approximately 0.1g/cm^3 . The samples used in this study were from the bottom cushion, part number 272011. A comparable polyurethane foam to which a flame retardant had been added was also examined. A carbon-black filled natural rubber was used to test the respirometer and compare the results obtained by the respirometer with the UOC method.

Compressive Strength. Compressive strength of the foam was measured on an Instron 5500R instrument using foam cubes with dimensions of $2.5 \times 2.5 \times 2.5\text{ cm}^3$. The foam was twice compressed to 40% of its initial height and then compressed to 50% of its initial height and the force recorded. Foams are often compressed multiple times for improved reproducibility and this procedure had been adopted early in the mechanical testing program for these foams.

Respirometer. The respirometer, an Oxzilla II Dual Absolute and Differential Oxygen Analyzer from Sable Systems International (Las Vegas, NV), is based on sensitive fuel cell detectors. The output of each fuel cell detector depends on the concentration of oxygen in the air stream directed to that fuel cell. The output of the fuel cell connected to the sample chamber is subtracted from the output of the fuel cell connected to the reference flow and the difference is used to calculate the amount of oxygen that was consumed by the polymer sample during aging. A simplified outline of the arrangement is shown in Scheme I. The respirometer and a gas multiplexer (also purchased from Sable Systems International) are controlled by a laboratory PC, which was also used to record the data. Ultrapure air was supplied by Matheson Inc. A source of compressed air with consistent composition was necessary because the instrument was in a laboratory with cryogenic equipment which perturbed the ambient oxygen levels. The same cylinder of air was used to fill and analyze a sample, since oxygen levels fluctuated somewhat from cylinder to cylinder. The cylinder air was passed through a column of Dririte and then split into two flows, each regulated by a mass flow valve. One flow went directly to the respirometer, while the second flow was directed by the multiplexer through either a short bypass loop or through the sample chamber. After passing over the sample, this flow was directed through Dririte and Ascarite to remove water and CO_2 produced during the degradation process and then to the respirometer. These lines were made as short as possible in order to minimize the time required to flush the chamber. A pressure-vacuum manifold with a pressure transducer was used to monitor the operation of the system and to remove the ambient air from short sections of the gas pathway that were exposed during connection of a sample chamber to the system. The sample chamber consisted of a stainless steel tube 7.5 cm long by 1.5 cm inside diameter fitted to a Conflat flange at each end. The chamber was fastened to stainless steel Swagelok valves, outfitted with Conflat flanges, by means of gold-plated copper seals. The total sealed volume of the chamber was 19.1 cm^3 .

Scheme I. Diagram of the respirometer and associated gas supply

Procedure. A known amount of polymer was placed in a sample chamber. The sample was typically 0.2 cm or less in thickness for the bulk natural rubber and 0.4 cm or less for the polyurethane foam in order to reduce diffusion limited oxidation effects [10,19]. The vessel was evacuated; cylinder air at 40 cm³/min was passed over the sample for several minutes and the chamber sealed. After an interval of at least one hour, air was again passed over the sample in order to completely eliminate any contribution originating from ambient air dissolved in the sample. The chamber was removed from the manifold and placed in an air-circulating oven. After 20 minutes, one of the chamber valves was momentarily opened to equilibrate the pressure at elevated temperature so that the oxidative aging and compressive force aging were both conducted at the atmospheric pressure of Albuquerque (630 torr). After aging, the sample chamber was reconnected to the manifold and the short sections of the connecting gas pathways that had been exposed to atmosphere were evacuated and refilled with cylinder air. The respirometer was stabilized by passing air through the bypass loop and setting each of the outputs of the respirometer to a nominal value of 20.95% oxygen.

At time “0”, the multiplexer was instructed to switch the air flow from the bypass loop to the sample chamber. The difference between the oxygen concentration of its air flow and the reference air flow was recorded as a function of time. The difference reached a maximum after 60 seconds, and recovered after approximately 3 minutes, although the flow was usually continued for at least 5 minutes in order to obtain a stable baseline. There was some concern that there would be “dead” spaces in the chamber that would not readily exchange with the air flow. After the initial air flow, samples were allowed to equilibrate from 2 to 16 hours and then flushed again. The second experiment showed levels of depletion ranging from 1 to 5% of the initial experiment. These levels, which were a combination of additional aging at ambient temperature, incomplete exchange during the first flush, and a dissolved oxygen effect, were not considered significant. The dissolved oxygen effect originates from the diminished concentration of oxygen in the polymer at the end of the aging experiment due to the reduced partial pressure of oxygen in the headspace. A third experiment showed no contribution from incomplete exchange or dissolved oxygen.

Calculation. The volume of oxygen at STP was calculated by multiplying the integral of the oxygen concentration vs. flow time (units of percent oxygen $\times$ minute) by the flow rate (40 cc STP/minute) and dividing the result by 100%. The volume of oxygen at STP was then converted to moles of oxygen and divided by the sample weight in grams and the aging time in seconds to provide an oxidation rate in units of mol O₂ STP/g sample/s.

Calibration. Samples with a known excess of oxygen were prepared by adding 20 to 40 torr of oxygen to an empty sample chamber and then completing the fill with cylinder air. The oxygen excess in cm³ STP could be calculated from the partial pressure and volume of oxygen. The calculated excess agreed with that measured by the respirometer to within 10%. The flow rates of the mass flow meters (a crucial parameter in all oxygen depletion calculations) were ensured by continuously monitoring the rates with Matheson gas flow meters and occasionally performing water displacement experiments with an inverted volumetric flask. Comparisons of the respirometer and UOC methods on actual samples are presented in the following section.

3. Results and Discussion

3.1 Compressive force measurements

The polyurethane foam used for the bottom cushion, part number 272011, of the H1259 storage container is designed to protect its contents from shock and vibration. An important property for the performance of this task is the compressive strength of the foam. As described in the experimental section, the foam is compressed twice to 40% of its initial height and during the third cycle compressed to 50% of its initial height and the force measured. The compressive forces of foam samples as a function of aging time and temperature are shown in Fig. 1. Note that the limited data available at 80°C means the results for this temperature are very uncertain. In drawing the curve for 80°C aging, more weight was given to the data taken of the foam aged for the longest period of time, 1049 days. Additional measurements were performed on samples that had been aged at 65 and 50°C for up to 1049 days, but the compressive force had not changed sufficiently for clear trends to be established.

The shapes of the compressive strength curves for samples aged from 95 to 140°C are reasonably similar. The similarity of the curves suggests that comparable aging processes are occurring at each temperature and that a time-temperature superposition is possible. The acceleration factor, a_T , for an aging process at a particular temperature is defined as the multiplicative factor that needs to be applied to the time axis in order for the data at that temperature to superimpose with the data at a chosen reference temperature. For the compressive strength of the polyurethane foam, we chose 95°C as the reference temperature. The time-temperature superposition plot is shown in Fig. 2. The data points for the various temperatures fall reasonably well on the smooth curve.

If the aging process is described by an activation energy, then the logarithm of the acceleration factors shown in the legend of Fig. 2 should be linear when plotted versus inverse temperature. Such a plot is shown in Fig. 3 where the slope of the linear fit provides an activation energy of 18.6 kcal/mole. A straight line extrapolation of the data is often extended to ambient temperatures (23°C is equivalent to $1000/T = 3.376$) and an acceleration factor for ambient conditions determined. This acceleration factor can then be used to predict the aging behavior of the material as a function of time. For this material, the extrapolation needs to be performed over an extended temperature range. This extrapolation can lead to considerable uncertainty because often the acceleration factors begin to curve upward at lower temperatures so that a straight line extrapolation predicts an acceleration factor smaller than the actual acceleration factor and thus predicts slower aging than would actually occur.

3.2 Ultrasensitive oxygen consumption

Fig. 4 shows the oxygen consumption of the polyurethane foam as a function of aging time for temperatures ranging from 50 to 125°C. The lines represent power law fits to the data sets for each temperature. The R values for the fits range from 0.982 to 1.000 and average 0.995. The power law exponents (slopes in Fig. 3) are 0.98, 0.83, 0.97, 0.90 and 1.10 for the 65 to 125°C data sets, with an average exponent of 0.96 ± 0.10 . The exponents exhibit no strong trend with respect to temperature and their average values do not differ in a statistically significant way from the value of 1.0. Thus we conclude that for the conditions examined, the oxidation rates do not depend on the extent of degradation.

Fig. 5 shows the time-temperature superposition plot for oxygen consumption of the polyurethane foam measured by the UOC method. The data superimpose reasonably well and are fit by a straight line that was forced to have a slope of 1.0. The acceleration factors for the time-temperature

superposition are shown in the legend of Fig. 5 and are plotted versus inverse temperature in Fig. 6. The acceleration factors exhibit a moderate amount of curvature at the lowest temperatures. Curvature in the lower temperature regime of an acceleration factor plot is seen for many polymers [20]. Although curvature is often attributed to a change in aging mechanisms, the effect may be somewhat more subtle. The aging process for a real polymer normally consists of multiple chemical reactions both in series and in parallel. Curvature is then expected if the various reactions have unique activation energies so that different reactions are rate limiting at high and low temperatures, although the overall reaction scheme may remain constant. Note that the curvature in this plot is not as pronounced as is sometimes observed because we do not have oxidation rate data for temperatures approaching ambient. Exposure times at room temperature are quite lengthy because the total weight of foam that can be placed in the sample chamber is limited. Attempts to increase the sample mass by cutting the material into small pieces and compressing the sample resulted in significantly faster oxidation rates than observed for intact uncompressed samples.

3.3 Oxidation rates by the respirometer

Fig. 7 shows the oxygen deficit trace from a sample chamber containing 0.207 g of carbon filled natural rubber that had been aged for 16 hrs at 80°C. The dual detectors were first balanced with identical air streams flowing through both channels. At $t = 0$, one of the air streams was redirected to the sample chamber by the multiplexer unit. After approximately 40 seconds the oxygen deficit became apparent, reached a maximum at 60 seconds and then began to decrease. The hatched area represents the total oxygen deficit which was calculated to be $0.0819 \text{ cm}^3 \text{ O}_2$ at STP or $117 \text{ } \mu\text{g O}_2$. This amount of oxygen corresponds to an oxidation rate of $3.06 \times 10^{-10} \text{ mol O}_2 \text{ STP/g sample/s}$.

There was some concern that the air in the chamber would not be fully displaced in a reasonable period of time. Note that with an air flow of $40 \text{ cm}^3/\text{min}$, the volume of air flowing over the sample would be more than twice the volume of the sample chamber (19.1 cm^3) during each minute of flow. Thus it seems reasonable that the deficit appears to be fully recovered approximately two minutes after the maximum deficit. The completeness of the exchange was also confirmed by allowing the chamber to equilibrate for times ranging from 2 to 16 hrs. After equilibration, the experiment was repeated with the detector set for increased sensitivity. The second traces were always less than 5% of the first trace and were typically in the range of 1 to 2% of the first trace. Much of the contribution to the second trace could be attributed to the oxygen deficit of the air that was dissolved in the sample. This air would not exchange with the gas flow during the several minutes of the experiment, but would exchange during the equilibration period and could then be detected during the second experiment.

Table I shows a comparison between oxygen consumption experiments on natural rubber performed by the respirometer and by the UOC methods at an aging temperature of 95°C. The agreement between the two methods is reasonable and demonstrates the validity of the respirometer experiment. Note that the experimental scatter is significantly less for the respirometer experiments. We attribute this to the greater sensitivity of the respirometer and its stability over time. The sensitivity can be appreciated by the lack of noise in the oxygen deficit trace in Fig. 7. The calibrations of the respirometer and the air flows were checked several times over the 6 month operation of the instrument. Other than balancing the response of the two detectors to a nominal value of 20.95%, adjustment of the instrument was not required during this time.

The oxygen deficit trace of a polyurethane foam sample (cut from part no. 272011) aged at 23°C for 555 hours is shown in Fig. 8. The low density of the foam limited the amount of sample that could be easily placed into the chamber to 1.07 g. Additional material would have lead to compression of the foam and obstruction of the free flow of air through the chamber. Aging at room temperature

represents the lowest oxidation rate that needs to be measured for typical aging conditions. The oxygen deficit range of the respirometer was set to maximum sensitivity. Although the trace exhibits considerable fluctuation (the response was not time-filtered), the integral represented by the crosshatched area could be reliably measured. Later in the paper, we will discuss the reproducibility of repeat measurements. The total deficit equals $0.00149 \text{ cm}^3 \text{ O}_2 \text{ STP}$ or $2.1 \text{ } \mu\text{g}$ for the 1.07 g sample and predicts an oxidation rate of $3.12 \times 10^{-14} \text{ mol O}_2 \text{ STP/g sample/s}$.

The goal of this study is to determine acceleration factors for the oxidation rate of the foam over a wide temperature range, including room temperature, so that high temperature aging behavior can be reliably extrapolated to room temperature. We have demonstrated that the respirometer can be used to measure these oxidation rates in a relatively short period of time. One complication that needs to be considered is the possibility that the oxidation rate of the foam changes during the aging process. This factor is typically handled by performing a time-temperature superposition of all of the temperature measurements. The high temperature measurements are conducted for a sufficiently long period of time so that the entire degradation process is mapped out on the time-temperature superposition plot. Changes in the oxidation rate with time are then identified by a change of slope in the oxidation rate. A considerable effort was expended measuring the oxidation rate of the foam by UOC methods before the respirometer became available to us. These results presented in the previous section demonstrated that the oxidation rate does not depend on the extent of aging.

Because the UOC experiments demonstrated that the oxidation rate is largely independent of the extent of oxidation, we measured the oxidation rates with the respirometer for only limited periods of time at various temperatures. The oxidation rates as a function of inverse temperature are shown in Fig. 9. The experiment was repeated 7 times at 23°C using exposure times ranging from 236 to 555 hrs in order to determine the reproducibility of the measurement under the most stringent requirements. The average oxidation rate at 23°C was $3.4 \times 10^{-14} \text{ mol O}_2 \text{ STP/g sample/s}$ with a standard deviation of $\pm 0.6 \times 10^{-14} \text{ O}_2 \text{ STP/g sample/s}$. Four separate samples were used for the 7 measurements with no observable variation of oxidation rate from sample to sample. These results demonstrate that the respirometer can reproducibly measure very slow oxidation rates of low density materials at room temperature in a relatively short period of time. The oxidation rates at each temperature were averaged and used to calculate acceleration factors that were normalized to 1.0 at 95°C . The results versus inverse temperature are shown in Fig. 10. The acceleration factor plot exhibits some curvature in the lower temperature region of the curve. The activation energy of the relatively linear region between 50 and 110°C is 22.0 kcal/mole , comparable to the 18.6 kcal/mole measured for the compressive force.

The acceleration factors shown in the legend of Fig. 10 are plotted vs. inverse temperature in Fig. 11 along with the acceleration factors determined by the compressive force and UOC experiments. The acceleration factors determined by the various techniques correlate reasonably well as a function of temperature. The line fit exhibits curvature similar to that shown in Fig. 10 for the oxidation rates measured by the respirometer because the low temperature region, 25 and 37°C , is defined solely by the respirometer data. The least squares fit of all the acceleration factors for temperatures ranging from 50 to 140°C yields an activation energy of 20.8 kcal/mole with an R value of 0.95. We believe that this is reasonably good correlation for three techniques that measure both mechanical and chemical properties over a range of nearly 3 orders of magnitude.

3.4 Lifetime prediction

The oxidation rate acceleration factors at room temperature can now be used to predict the behavior of the compressive strength as a function of time at room temperature. The upper limit for the compressive force at 50% is specified as 7.5 psi. At 95°C, the time required to reach this state is approximately 5000 hrs. Using the ratio of acceleration factors at 95 and 23°C from Fig. 11 (1.0 and 0.002), we predict that at 23°C, the compressive strength of the foam will reach 60 kPa after 2,500,000 hours or approximately 280 years of service. Similar calculations estimate service lifetimes of 110 and 40 years of service for temperatures of 37 and 50°C, respectively. These predictions assume that the compressive strength is related to the oxidation rate at these lower temperatures in quantitatively the same fashion as they are related at 95°C. Similar assumptions coupling oxidation rates to mechanical properties of polymers have proven quite useful for a variety of polymers and clearly the relationship could depart significantly from ideality before oxidative aging became an issue at room temperature.

The obvious manner to increase confidence in these predictions is to continue to measure compressive forces of these materials for longer period of times at lower temperatures in order to determine if the acceleration factors for compressive force and oxidation rate continue to correlate. The aging time required for obtaining reproducible changes in compressive strength at even 80°C makes it difficult, however, to test the relationship in this time and temperature regime. On the other hand, the lengthy time required to observe significant changes at this temperature attests to the long life of the foam.

3.5 Flame retardant polyurethane foam

We were provided with samples of a polyurethane foam, similar to part number 272011, to which a flame retardant had been added to the formulation. These samples became available during the time that we were performing UOC measurements. A comparison of the oxidation rates of the polyurethane foam with the oxidation rates of the flame retardant polyurethane foam is shown in Fig. 12. There's considerable scatter in the data of the foams, especially the flame retardant foam, but it's obvious that the oxidation rate of the foam has not been accelerated by the addition of the flame retardant. It appears that the additive has caused an overall reduction in the oxidation rate of the polyurethane and therefore we expect that the life of this foam should be at least as long as the original polyurethane.

4. Conclusions

The increase in compressive strength as a function of aging time of the polyurethane foam used for the bottom cushion of the H1259 storage container has been measured at temperatures from 80 to 140°C. Although an Arrhenius extrapolation to ambient temperature could be performed, considerable uncertainty would be introduced by such an extrapolation over an extended temperature range. Measurements of the polyurethane's oxidation rate by UOC and respirometer methods were used to improve the confidence in the extrapolation.

Although the UOC method has been used extensively in the past, this method suffered from lack of sensitivity and considerable scatter for these low density foams. For this reason we adapted a respirometer for measuring the extremely low oxidation rates of polymers and found that it offers several advantages. The exact sensitivity advantage is difficult to quantify because sensitivity is always a tradeoff between speed and accuracy. A reasonable comparison between the two methods can be made by observing the actual times used to perform measurements at 37°C (the lowest temperature completed by the UOC method). The UOC method required nearly 6 months of aging while the respirometer required 1 week of aging. Along with this factor of 25 in decreased experimental time, the standard deviation of the respirometer data was typically 3 or 4 times less than that of the UOC method, implying an additional decrease in experimental time for comparable accuracy. Sensitivity is essential when measuring oxidation rates at low temperatures and is especially important when investigating materials such as low density foams where the total oxygen depletion is reduced compared to an experiment with bulk materials. The increased sensitivity enables the aging time, and thus the total time to complete the experiment, to be reduced and also permits less material to be placed in a chamber, thereby minimizing the effects related to oxygen solubility and gas transfer. By using only 1 g of foam in a chamber volume of approximately 20 cc, the gas dissolved in the foam represents only 0.5% of the total gas assuming a typical solubility constant for oxygen of 10%. This small fraction of dissolved oxygen eliminates the need for a solubility correction. Finally, the improved sensitivity and reduced experimental time implies that the partial pressure of oxygen is reduced to a lesser extent during an experiment. This decreases the uncertainty introduced by the possible dependency of the oxidation rate on the partial pressure of oxygen. The respirometer extends our capabilities to lower temperatures and less dense samples, shortens the aging time and improves the accuracy of oxidation experiments.

The oxidation rates measured by the respirometer were used to derive acceleration factors for the oxidative aging process down to ambient conditions. These acceleration factors were then used to derive lifetimes for the compressive strength of the cushion as a function of aging temperature. Both the normal polyurethane foam and the foam containing a fire retardant additive exhibited slow oxidation rates implying exceptionally long service lifetimes.

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6. Tables and Figures

Table I. A comparison of the oxidation rates of a carbon filled natural rubber at 95°C as measured by a respirometer and the UOC method.

	Respirometer (mol/g/s x 10 ⁻¹⁰)	UOC (mol/g/s x 10 ⁻¹⁰)
	12.6	14.8
	12.4	11.5
	12.3	19.0
	11.8	15.4
	11.5	
	_____	_____
average	12.1 ± 0.5	15.2 ± 3.1

Figure 1. The compressive force at 50% of the polyurethane foam as a function of aging time for various temperatures.

Figure 2. The time-temperature superposition of the compressive force for the polyurethane foam. The shift factors for the various temperatures are shown in the legend.

Figure 3. The acceleration factors for the compressive force at 50% for the polyurethane foam.

Figure 4. The oxygen consumption of a polyurethane foam measured by the UOC method as a function of aging time for various temperatures.

Figure 5. The time-temperature superposition of oxygen consumption of the polyurethane foam measured by the UOC method.

Figure 6. The acceleration factors versus inverse temperature for the oxygen consumption of the polyurethane foam measured by the UOC method.

Figure 7. The respirometer recording of the oxygen deficit trace of 0.207 g carbon filled natural rubber that has been aged for 16 hrs at 80°C.

Figure 8. The respirometer recording of the oxygen deficit trace of 1.07 g polyurethane foam that has been aged for 555 hrs at 23°C.

Figure 9. The oxidation rates of a polyurethane foam measured by the respirometer versus inverse temperature.

Figure 10. The acceleration factors versus inverse temperature for the oxidation of a polyurethane foam measured by the respirometer.

Figure 11. The acceleration factors for the compressive force, the oxidation rate measured by the respirometer and the oxidation rate measured by UOC for a polyurethane foam.

Figure 12. A comparison of the oxidation rate of the polyurethane foam with a flame retardant polyurethane foam.

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