Sealing force response and its relationship to leakage

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Executive summary

People evaluate the sealing force response of materials to try to estimate when leakage might occur. This is often based on correlated relationships between sealing force responses and actual sealing performance. This paper intends to try to provide a more direct relationship between sealing force and leakage and to show what kinds of factors might affect this relationship.

This study aims to provide data and test approaches that measure sealing force over the full temperature range, from high temperatures where seals age, to low temperatures where seals leak. In many cases, people assume that the seal's ability to prevent leakage at low temperature is based on the Tg or TR10 of the material, but this is only useful for new materials. As materials age, their ability to seal at low temperature changes along with their sealing force response curves.

This paper also will discuss sealing configurations and the relationship between the sealing forces developed upon compression for static seals and leakage. It also will note the effect of changes in both the magnitude and rate of deformation, as well as temperature on the sealing force response and leakage. All of these factors will be integrated into concepts that can be used to try and predict performance of static seals in real world applications.

This project seeks to elaborate on the concept of sealing and leakage, how it is impacted not only by material properties, but also viscoelastic responses and configuration and aging effects. If leakage occurs in a sealing application, when is a seal failure a material issue, and when is it a design issue? And what test approaches might one use to delineate the reasoning for the answer?

This paper does not have answers for all situations, but hopes to provide some perspectives and testing approaches that might be considered to evaluate both material responses and configuration effects, to enable the prediction of sealing performance in an application. The objective is to enable the evaluation of different materials in a range of configurations to allow the selection of a given elastomer and seal design for a specific sealing configuration, to not only maximize its performance, but to enable prediction of its service life in applications based on defined qualifications.

TECHNICAL NOTEBOOK
Edited by John Dick

Sealing force and leakage

People often hear about the term "sealing force" and might equate it with the concept of sealing with rubber components in an application in order to prevent leakage. It might also be considered as a term often used in a standard test for sealing capability known as compression stress relaxation (CSR). I would suggest that it is the resultant force a rubber specimen exerts against another surface when it is compressed between two surfaces and used to prevent leakage of fluids between two adjacent control volumes.

This could be a result of the compression of linear seals between two surfaces that might have parallel faces or have a circular cross-section like O-rings. It could also be where circular shapes are being compressed in a radial fashion where there is an ID-OD constraint around a centerline axis. It could even be both, where an O-ring or profile seal is compressed in an axial configuration in a groove, where it exerts not only a force perpendicular to the compression faces, but also laterally and radially when there is a lateral constraint, where some type of groove or channel is used to hold or constrain the seal.

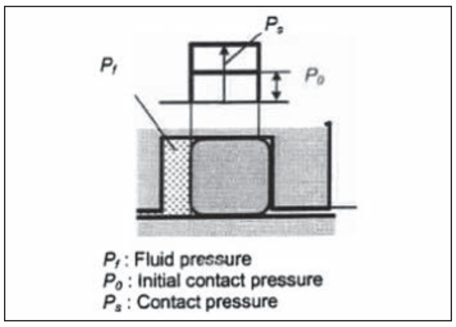
This force—along with the shape and conformability of the rubber component—provides a contact pressure over the contact surface that promotes intimate contact between the rubber seal or component, which prevents fluids from passing by the seal at that location. The concern with the relationship between sealing force and leakage is that although sealing force is a measureable quantity and useful for evaluating sealing, the real concern should be the sealing pressure profile over a contact area and its surface roughness.

Sealing pressure is sealing force divided by the contact area (A) over which the force is being projected. With seals containing flat faces and straight edges (such as cylindrical shaped washers) being compressed between two parallel plates, the sealing pressure should be fairly uniform across the whole contact surface and be capable of being calculated from the measured sealing force and a calculated contact area.

In a similar configuration with an O-ring of comparable size, although the force being applied could be the same, the pressure being applied would vary across the face of the seal. The maximum pressure being exerted would be at the center of the cross-section of the seal, or with profile seals of different shapes, the location on the seal would be where the maximum compression across the profile is occurring. This sealing pressure is what provides intimate contact between the surfaces and also provides a force which is capable a resisting a fluid pressure that might want to flow past the sealing interface.

In cases where higher fluid pressure is exerted, the lateral pressure being exerted may help to enhance the contact pressure in the sealing direction. This principle was noted in an SAE Paper in 2003 and shown in **Fig. 1**, where they suggest that leakage occurs when fluid pressure exceeds sealing pressure.[1]

Fig. 1: Leakage occurs when fluid pressure (P_f) exceeds sealing pressure (P_s).



In order for that sealing pressure to be effective at preventing leakage, it must first create intimate contact between the sealing material and all of its contact face, as well as preventing lateral forces from opening up the interface using fluid pressure to allow leakage past that interface. Of concern in these kinds of configurations is the uniformity and directionality of surface irregularities or defects.

These could be scratches, machining marks or porosity. The concern with these possible surface irregularities is their width, depth, length and directionality. The concern then becomes how much surface contact pressure might be required to create intimate contact over those surfaces and to prevent leakage. So seals must be sized with a specific shape and percent compression that they will provide enough contact pressure over a sufficient area to

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Tuckner

Prior to starting this business nine years ago, he had worked at Dyneon/3M for 28 years as a research and development, application development and materials engineer, specializing in fluoroelastomers and fluoroplastics. He has a bachelor's degree in chemistry and a master's degree in systems engineering from the University of St. Thomas.

He holds four patents and has written and presented numerous Society of Automotive Engineers and ACS Rubber Division papers in the areas of permeation, compression stress relaxation and sealing.

Fig. 2: Shape factor figures with calculations.

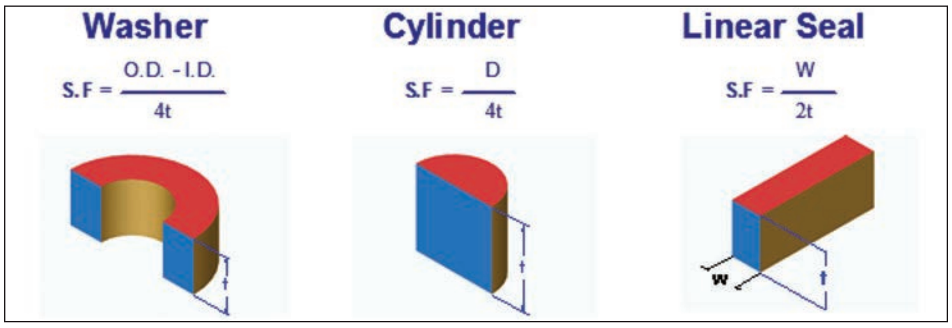
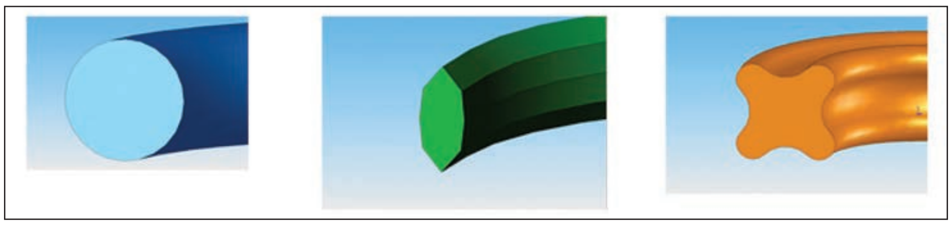


Fig. 3: Non-uniform compressed cross-sections shapes.



prevent leak paths across the seal face and the sealing areas of concern.

Sealing force response

The objective of initially outlining this sealing perspective, where leakage is based primarily on sealing pressure, is done because this specific response varies significantly with temperature. It also varies with a specific material's responses and the design configurations of shape, size and percent compression.

But once those are defined, it is temperature and its effect on the degradation of the material, as well as its effect on the sealing force that will determine when a seal might leak. It is important to realize how these different factors affect the sealing force response, so one can be able to delineate if a sealing failure is material issue or a design issue, or how much each might contribute to leakage.

Material response

In order to understand the sealing capability, if one assumes leakage is related to sealing force, one needs to know how sealing force varies with different configurations of size and shape. When testing a prismatic test specimen with what this study calls a "uniform compressed cross-section" in compression, one should be able to determine a "parametric" response of the elastomer's stress-strain response in compression.

A "uniform compressed cross-section" means that the contact faces under compression are the same through its total deformation and the sides of the test specimens are perpendicular to the contact faces. It is also preferred that the specimen be axi-symmetric and centered along the primary axis of compression. Cylindrical or washer type specimens correspond to this general guideline, but linear seals can also be defined in this way.

These types of test specimens can have their shape characterized by what is called their "shape factor." The shape factor value is calculated as the ratio of the area of one of the compressed contact surfaces to the area allowed to expand.[2] **Fig. 2** shows different shapes with the equations used to determine their shape factors.

Fig. 4: A range of test specimens of different sizes and shape factors.

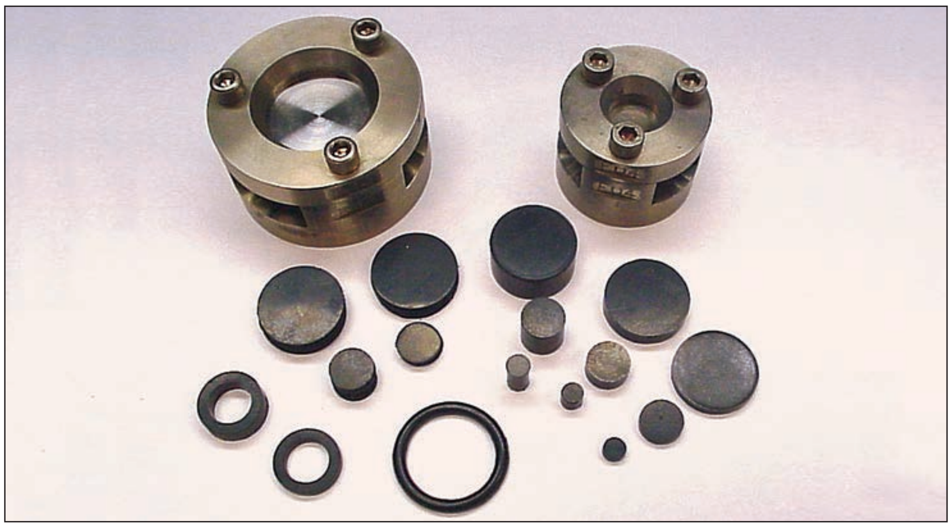


Fig. 5: Load deflection responses for different size test specimens.

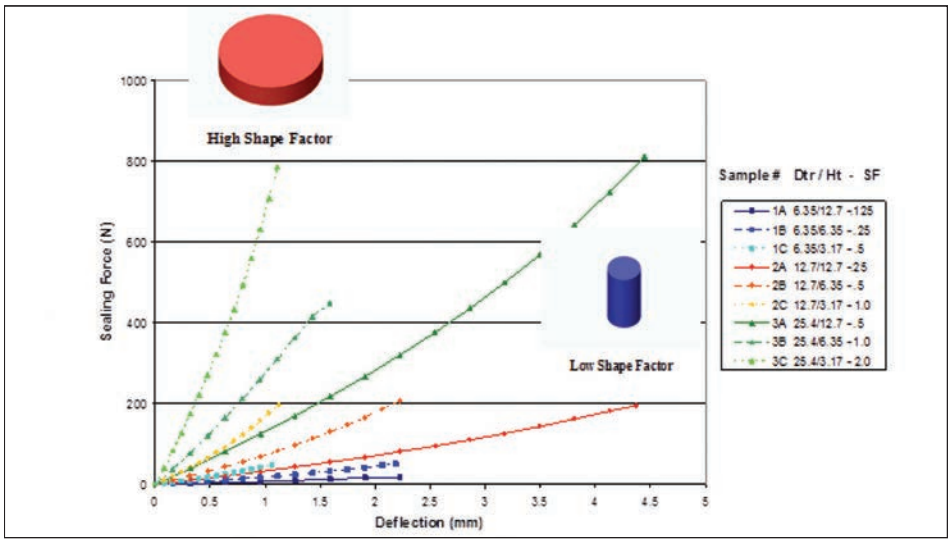
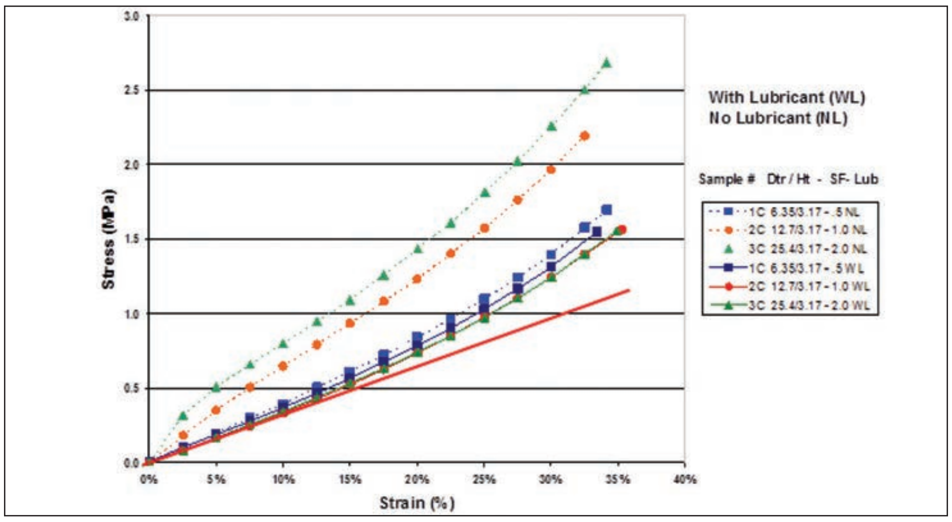


Fig. 6: Stress strain response with (WL) and without (NL) lubricant.



If one were to consider cylindrical test specimens, those that have small diameters in relation to their heights would have low shape factors. While those with large diameters and small heights would have large shape factors, by comparison, O-rings or seals with variations in their profiles, because their contact area changes with compression, they cannot be specifically defined with a shape factor value (**Fig. 3**).

The advantage of cylindrical test specimens with a uniform compressed cross-section is that regardless of their size and shape factor, they should provide the same stress-strain response in compression, within a certain reasonable shape factor range and level of strain.[3] A picture of test specimens of different sizes and shape factors is shown in **Fig. 4**.

This stress-strain response and its resultant calculated compressive modulus is what this study refers to as a "parametric" response, because you can develop values or parameters that can be used to predict the response of a test specimen of any shape and size within a certain range, and it would be considered a pure material response.

At low shape factors, the test specimens are susceptible to buckling, and at high shape factors, friction and lateral force can create a deviation from the primary material response. When tested for their load-deflection response in a near zero friction condition, these test specimens show different stiffness responses (slope of load/deflection) (**Fig. 5**).

When these same values of force (F) and deflection (δ) are normalized for their area (A) to determine their stress (σ=F/A), and their height (L) to determine their strain ($\varepsilon = \delta/L$), the test specimens show the same stress-strain response in compression over much of the strain range (**Fig. 6**).

This stress-strain response is generally fairly linear up to about 20 percent strain, which can be used to define a compressive modulus. This response is a characteristic material response and is useful because one can use any size of specimen to determine this value, and then use this value to predict the load (F) or the stiffness (load/deflection (F/δ)) response for any size cylindrical specimen (**Fig. 7**).

Regardless of size or shape factor, it provides the same response. This kind of response is similar to a tensile response, where tensile specimens of different sizes and shapes should have the same stress strain response within a reasonable range.[4] It is what this study considers a pure material response, as contrasted with "configuration effects."

Viscoelastic response

There are two primary viscoelastic effects: One is how load varies with deforma-

See **Sealing**, *page 16*

Sealing

Continued from page 15

tion, when deformed at different rates and over time, and the other is how these changes vary with temperature. Viscoelastic effects are a material response that varies with these different conditions.

For static sealing applications, these responses become less relevant, because the primary concern tends to be what the final load response is after a longer period of time, once the deformation has occurred to a specific level of strain, and after it has been exposed to its highest temperature for a short reasonable period of time. This condition results in what this study calls its "final intermediate equilibrium response" which is prior to any degradation due to aging. This final load should not be a result of the rate of deformation or temperature rise, but of the final level of strain and the highest exposure temperature for a reasonable time, to come to equilibrium and the final measurement temperature.

This kind of response is useful to define the crosslink level of the polymer, and the network and physical structure of the compound. **Fig. 8** shows the progression of loads through the initial compression and high temperature exposure, with the load point between interval three and four being its "final intermediate equilibrium load."[5]

Up to this point the load and strain should be recoverable upon reheating and cooling in an uncompressed state. After this point if degradation and/or volatile or extractable loss occur, it would not be expected to recover to its original shape.

This viscoelastic response can also be seen as being affected by the maximum temperature, where silicone test specimens were evaluated over a range of temperatures in **Fig. 9**. Even with temperatures where there was no noticeable degradation, it showed that the amount of force loss due to high temperature exposure and relaxation increased with increasing temperature.[5]

Configuration effects

Configuration effects are when particular responses may vary with configuration for a given material. An example of this might be where a given material is compressed to a defined level of strain, whose load can be estimated at a particular time from the CSR response, but whose load retention might vary over time, depending on the deformation strain.

Fig. 10 shows how the sealing force changes as a function of percent compression at different time intervals, which generally show sealing force increasing with increased strain.[6]

When this data is plotted as a function of percent retained sealing force in **Fig. 11**, you can see that at a low percent compression, you not only have lower sealing force, but you lose sealing force faster. At high temperatures, you may begin with higher sealing force, but you also lose it faster, so at some point in the exposure you do not have any higher sealing force than was seen at lower levels of strain. This type of configuration evaluation suggests there is an optimum region of percent compression for this particular material and environmental exposure.

Configuration effects can also be seen when one evaluates the effect of size and shape factor on the sealing force retention as shown in **Fig. 12**. When percent retained sealing force is plotted against shape factor (**Fig. 13**), it appears to show that test specimens with the lowest shape factor show the best retention of sealing force and that specimens with the same shape factor regardless of size show the same percent RSF.

In an additional study, using the same FKM materials and then also an HNBR sample, it showed the same response with the FKM, but a different response with the HNBR. The FKM again showed that test specimens of the same shape factor show the same level of retention regardless of size. With the HNBR compound, though, the percent RSF varied with the size of the test specimen, with larger specimens showing better retention.[7] A comparison of the results is shown in **Fig. 14**. Upon observing the test specimens in **Fig. 15**, it is easy to see why there was this difference.

With the HNBR aged in air, degradation occurs from the outside of the test specimen in, with the center portion showing minimal effects. In this case, the distance of progression of the degradation appears to be about the same for each of the test specimens, but it covers a larger percent of the projected area for the smaller test specimen, resulting in a larger loss in percent RSF.

This is a result of a difference in the mode of degradation between the two materials, where one degrades uniformly throughout the test specimens (as with the FKM), while the other degrades from the outside in because of what is known as diffusion limited oxidation (HNBR). In a similar study on O-rings, shown in **Figs. 16 & 17**, it could be seen that for silicones the percent RSF for O-ring with the same

Fig. 7: Compressive modulus calculations and relationships.

$$\text{Compressive Modulus} = \frac{\text{Stress}}{\text{Strain (\% Comp)}} = \frac{\dfrac{\text{Load}}{\text{Initial Area}}}{\dfrac{\text{Deflection}}{\text{Initial Thickness}}}$$

$$= \frac{\text{Load}}{\text{Deflection}} \times \frac{\text{Initial Thickness}}{\text{Initial Area}}$$

$$= \text{Sample Stiffness} \times \frac{\text{Initial Thickness}}{\text{Initial Area}}$$

$$\text{Load} = \text{Compressive Modulus} \times \text{Strain (\% Comp)} \times \text{Initial Area}$$

Fig. 8: Final intermediate equilibrium load response.

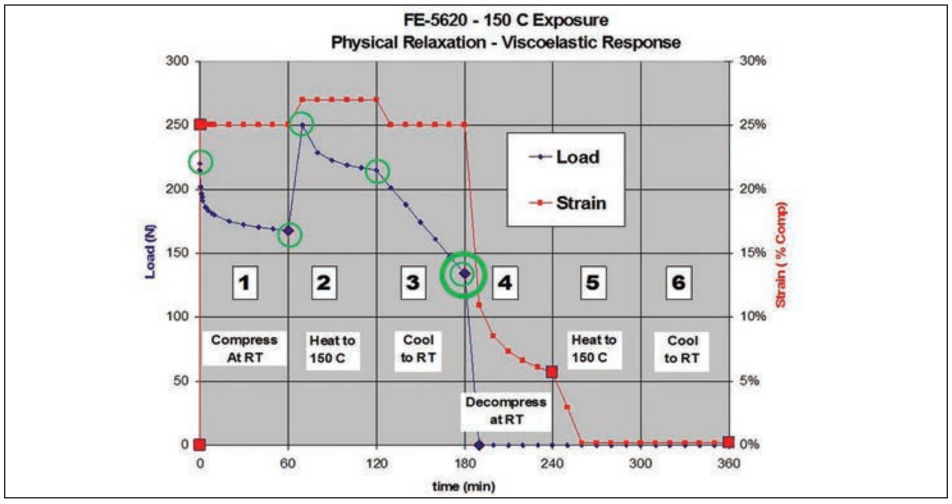


Fig. 9: Equilibrium load response as a function of temperature exposure.

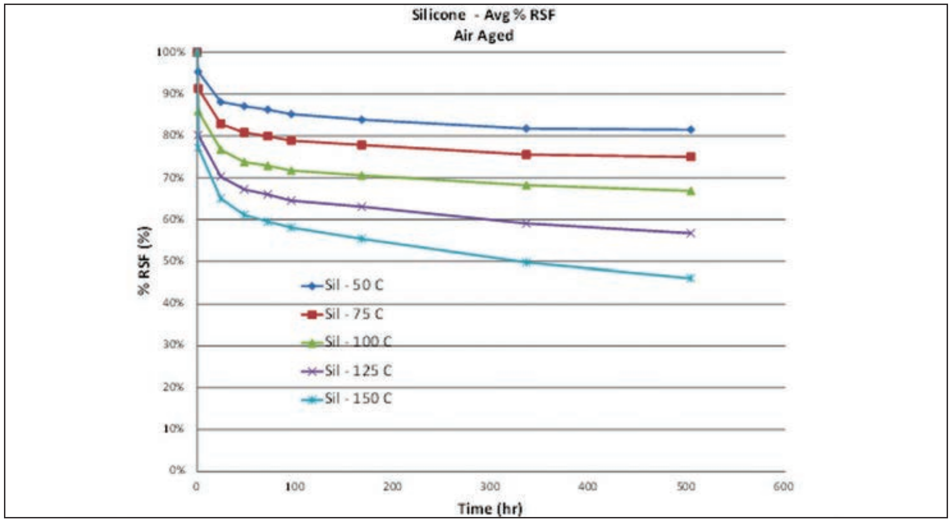


Fig. 10: Percent compression effect—sealing force.

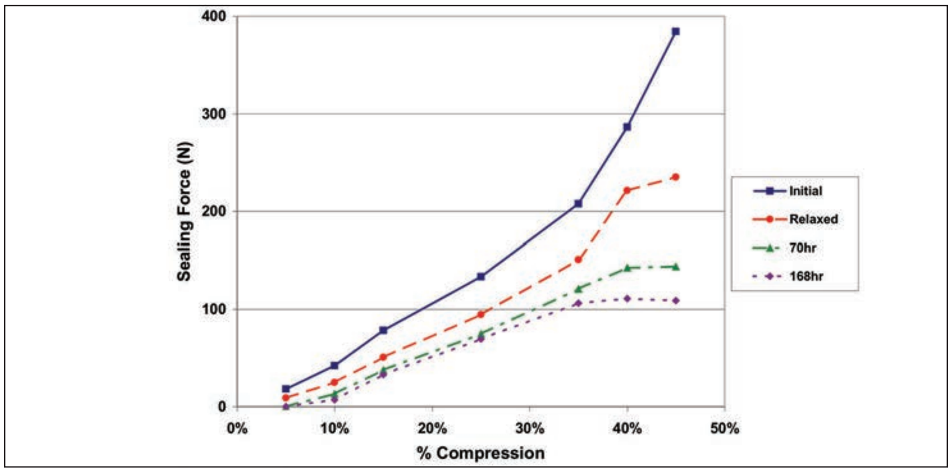


Fig. 11: Percent compression effect—percent RSF.

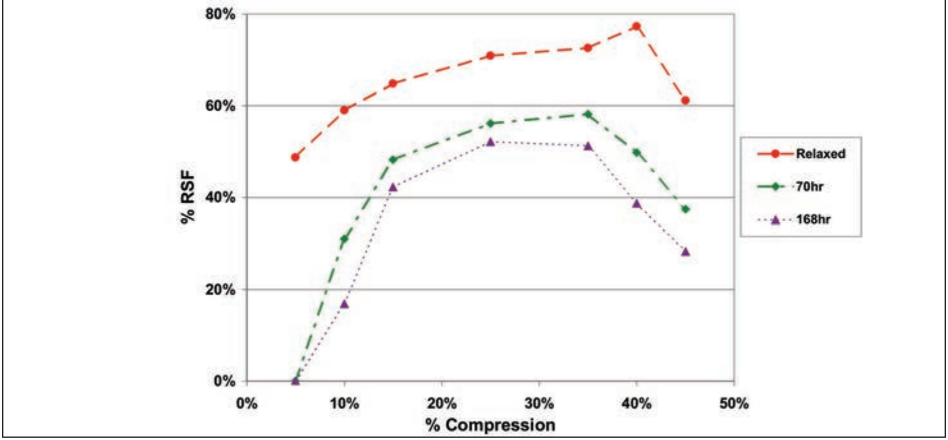
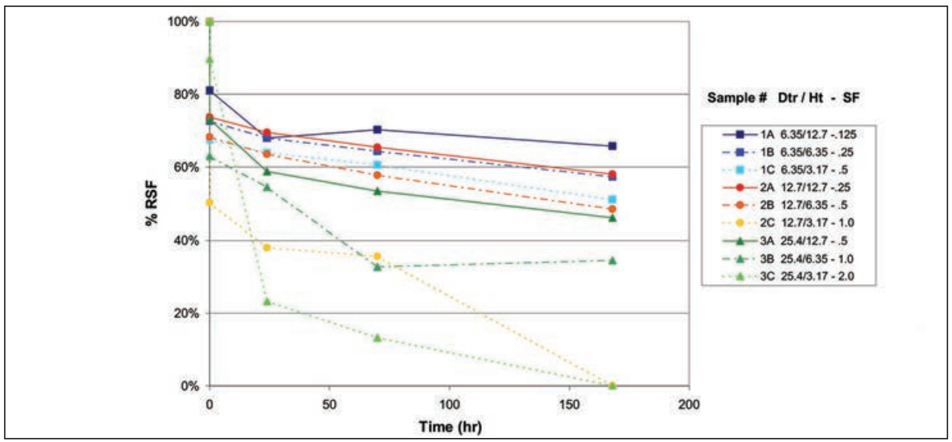


Fig. 12: Shape factor effect—percent RSF.



diameter, but different cross sections was similar, but for some nitrile elastomers, the percent RSF was better with the O-ring with the larger cross-section.[7]

With the silicone compound, once you know the mode of degradation and configuration effects, you can then have a better understanding of predicting its sealing response in an application with data, as shown in **Fig. 18**. This suggests that the change in sealing force, in addition to its initial material response, can be a function of the percent compression, size, shape factor and mode of degradation. It also suggests that this kind of testing can provide some insight as to how much of a change in sealing force might be a material issue or a configuration issue, and how much the chemistry and composition of the materials involved can affect the type and magnitude of changes in the sealing response.

Environmental effects

Environmental effects are the changes in the response as a function of time at temperature and fluid exposure. The fluid can be air, oils or coolants, or any fluid that might either have a swell effect or degradation effect on the elastomer or component. Swell effects tend to reduce the stiffness and compressive modulus of materials, but sometimes can be an equilibrium response, where when the fluid is absorbed, the response changes, but after the fluid is lost, such as evaporation of a volatile solvent, the original properties may be restored. A problem with some of these exposures, even in air is that there can be a volatile or extractable loss of material as a result of this kind of exposure, which changes the composition and integrity of the material.

More often, though, the biggest concern is degradation of the materials as a result of additional crosslinking of a material because of reaction with oxygen in air, or in the case of some fluoroelastomers, reactions with amine additives to form additional crosslinks which stiffen the polymer. This kind of reaction usually occurs from the outside exposed surface inward toward the center. The reaction with oxygen can also occur uniformly throughout the compound and result in additional uniform crosslinks or bond breakage to crosslinks or the polymer backbone.

A big part of some of the changes that occur with the properties are a result of material loss thanks to extraction or volatilization, and this typically results in a higher filler to polymer ratio, which has the same effect as having a higher filler level, and its effect on properties. When this occurs with test specimens or seals in compression, this volume loss results in test specimens or parts with a lower effective level of strain and a subsequent reduction in compressive force being exerted.

Thermal effects

Series unconstrained configuration

Although people may say or realize that the sealing force an elastomer test specimen or component changes with temperature, the real questions should be why does it change with temperature, how much does it change with temperature and how could this value be determined?

It is not just that the rubber has a high coefficient of thermal expansion, but how much higher is it in comparison with other materials, and how might this response vary with different configurations. If one goes back to the determination of the stress-strain response in compression with any linear elastic material, one should be able to determine the force a cylindrical specimen will exert when compressed to a specific level of strain.

Also, assume that rubber is a linear elastic material. If its intermediate equilibrium relaxed response is used over a reasonable strain range, then if a force or deflection of two different materials and shapes is applied in an unconstrained series configuration, the loads or deflections applied to the interfaces should be able to be determined (**Fig. 19**).

Series constrained configuration

In a second "series constrained" configuration, if it's assumed that the end plates are fixed and held at room temperature and two different sized cylinders are constrained between those fixed plates and heated to a higher temperature, both will want to expand, but they will need to reach an equilibrium force between them, so no movement is seen between the end plates (**Fig. 20**).

In this case, the amount of movement each would like to expand should be equal to the coefficient of thermal expansion times the change in temperature. And if the compressive modulus does not change throughout the small temperature range, with one material being a metal and the other being rubber, then the equilibrium position of the contact face between the two cylinders should be able to be determined.

This equilibrium force between them should be able to be determined by using the equations for stress-strain ($E = \sigma/\varepsilon$, $\sigma = F/A$, $\varepsilon = \delta/L$) and thermal expansion ($\varepsilon = \alpha(\Delta T)$) shown in **Fig. 21**. E is the value of the modulus of elasticity, Young's modu-

See **Sealing**, *page 18*

Fig. 13: Shape factor response—percent RSF.

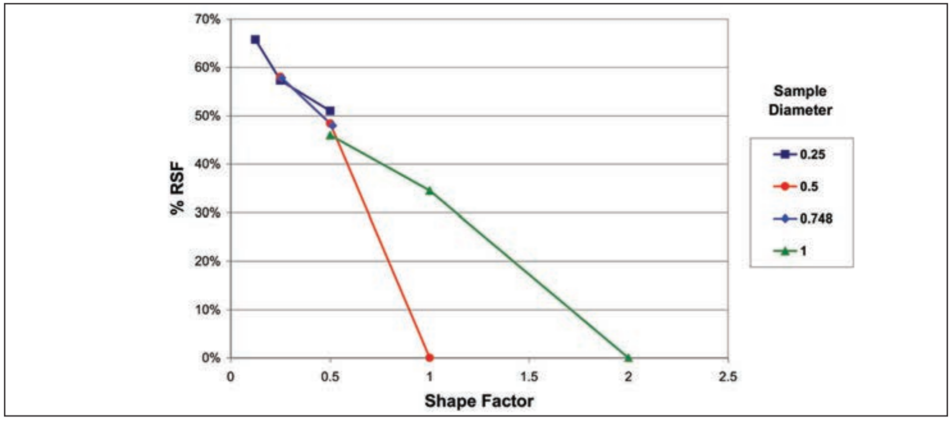


Fig. 14: Mode of degradation effects FKM vs. HNBR.

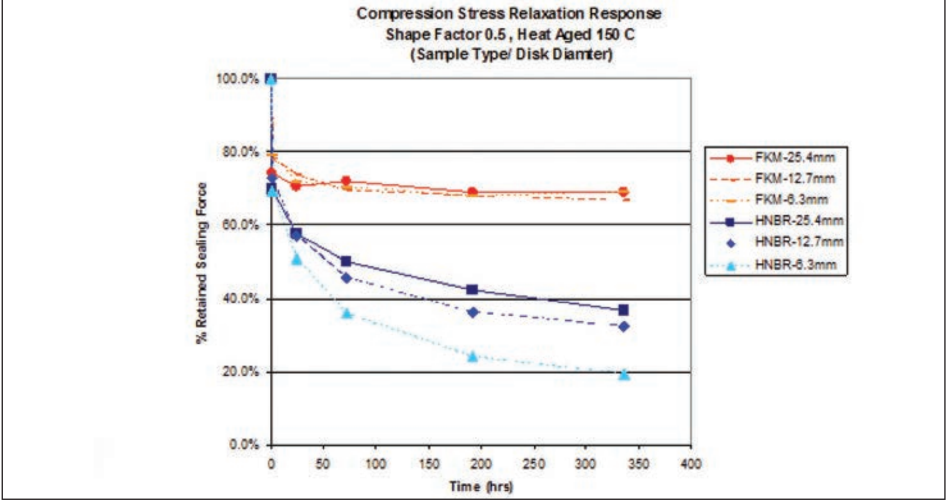


Fig. 15: HNBR—degradation of test specimens—diffusion limited oxidation.

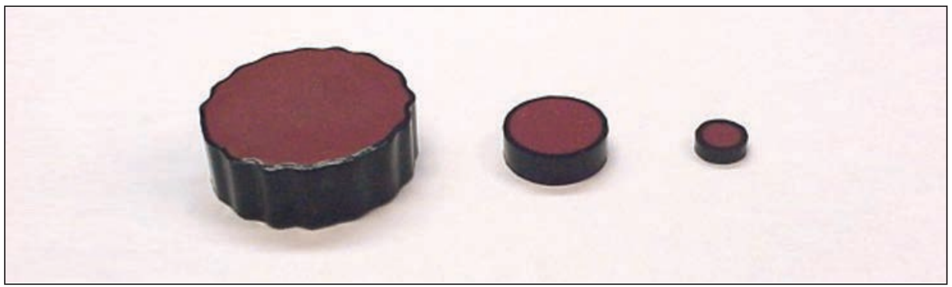


Fig. 16: Silicone—percent RSF as a function of O-ring thickness.

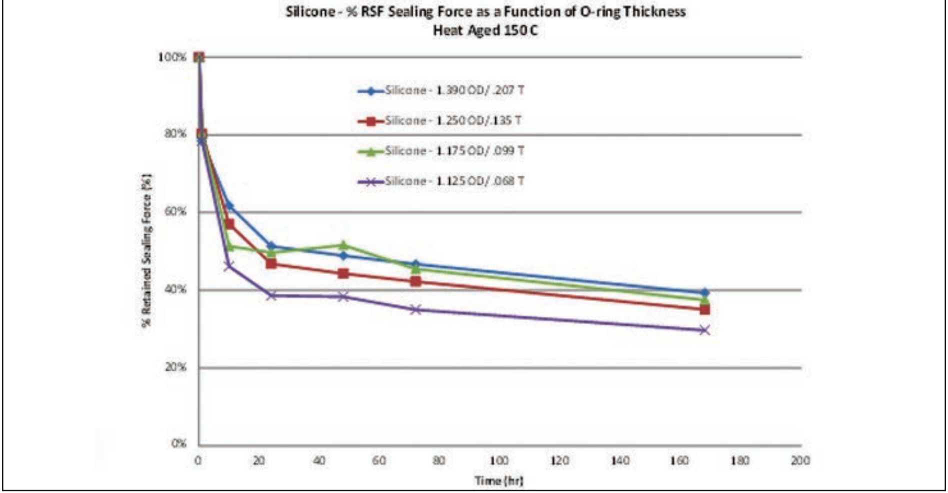


Fig. 17: Nitrile—percent RSF as a function of O-ring thickness.

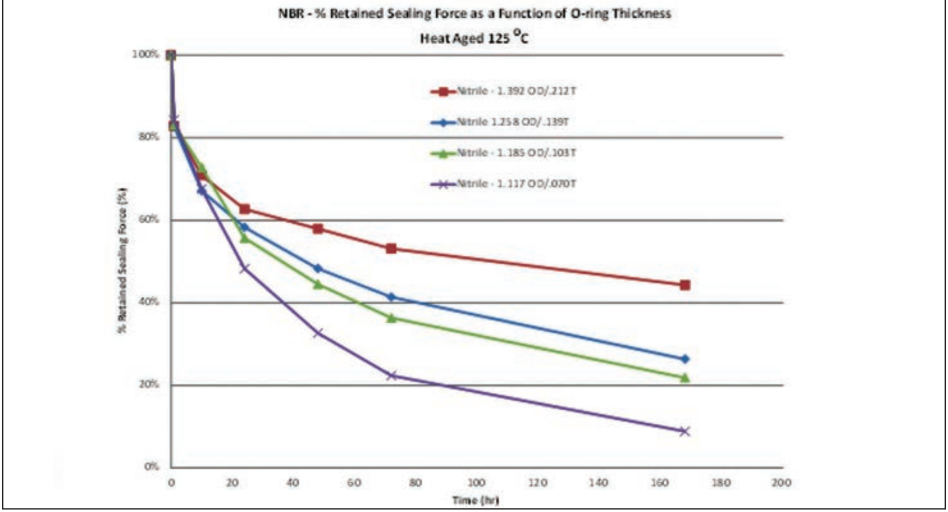
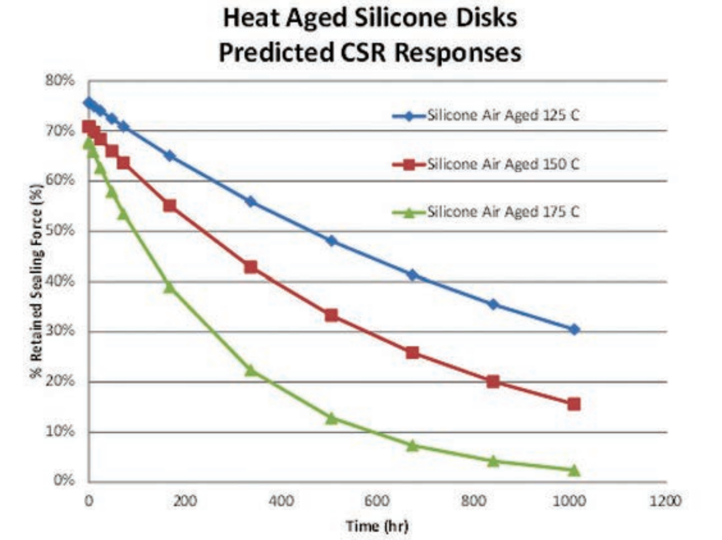


Fig. 18: Silicone—aged CSR response.



Sealing

Continued from page 17

lus or in the case of rubber, its compressive modulus where the other variables are represented by the stress (σ), force (F) cross-sectional area (A), strain or percent compression (ε), deflection (δ), length (L), coefficient of thermal expansion (α) and the change in temperature (ΔT).[4]

In most cases the stiffness of the metal with a similar diameter will create such a high force in expansion that most of the deformation or compression would take place in the elastomer cylinder. This could change some, though, if a larger relative diameter, shorter length rubber specimen with a higher compressive modulus is used, along with a longer metal tube with a small diameter and thin wall thickness.

Fig. 19: Series unconstrained configuration.

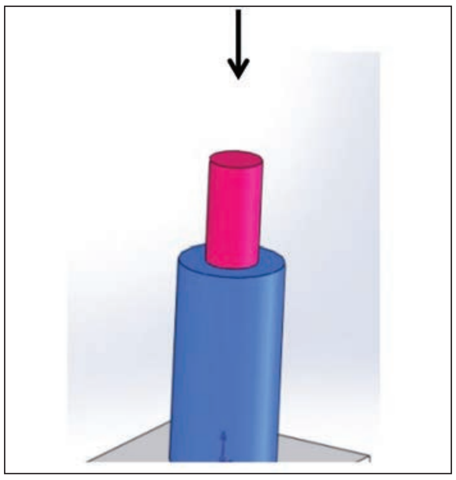
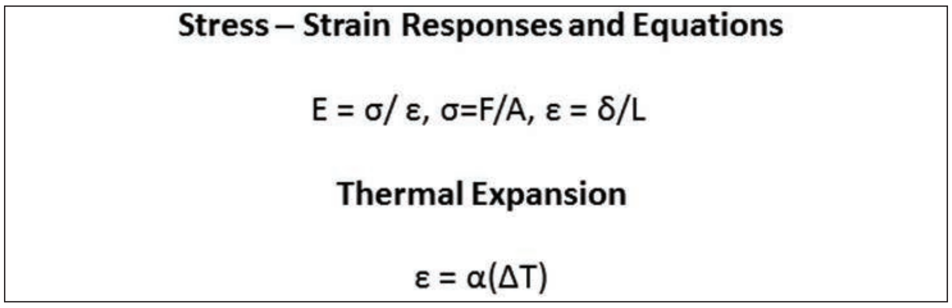


Fig 20: Stress—strain and thermal expansion equations.



Stress – Strain Responses and Equations

$$E = \sigma / \varepsilon, \sigma = F/A, \varepsilon = \delta / L$$

Thermal Expansion

$$\varepsilon = \alpha(\Delta T)$$

Fig. 21: Series constrained configuration.

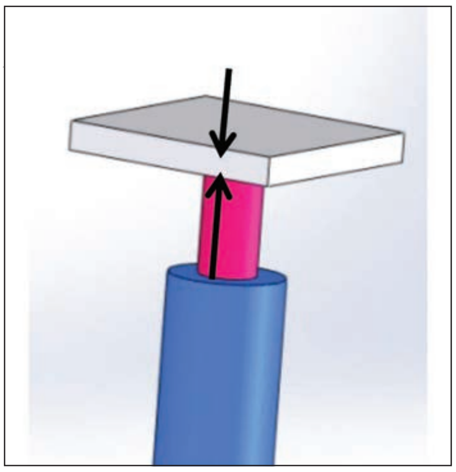


Fig. 22: Parallel constrained configuration.

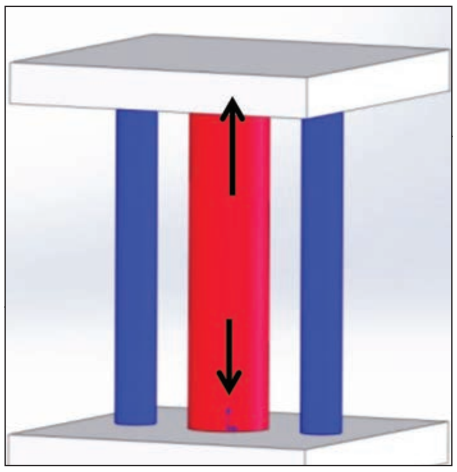
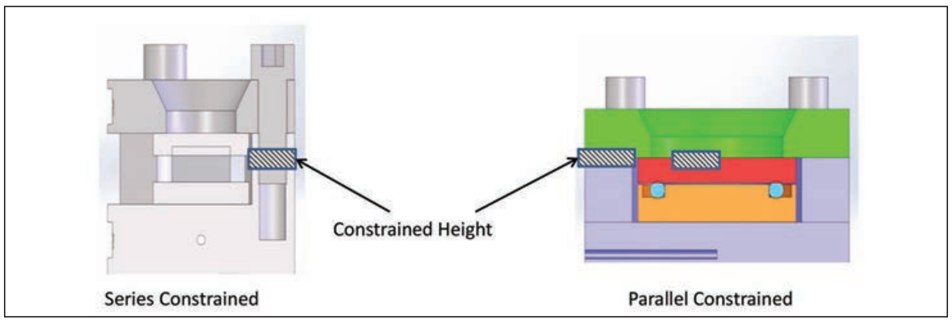


Fig. 23: CSR sealing configurations.



emphasize is that the forces generated are not due to one factor, but involve the size and stiffness of the constraining components and their coefficients of thermal expansion, in comparison to that of the rubber component or other constraining members in different kinds of configurations in sealing applications.

The two figures shown in **Fig. 23** are cross-sections of CSR fixtures. They show the compressed height of the elastomer component in relation to the serial or parallel constraining position within the CSR jigs. So it is not just the coefficient of thermal expansion of the elastomer that generates the higher contact force, but the difference in compressive modulus, the size and shape, and the coefficient of thermal expansion between the elastomer specimen and the constraining member of the configuration.

Thermal expansion considerations

In **Fig. 24**, the range of coefficients of thermal expansion of different materials can be seen. These are only typical values, and for rubber they can vary significantly depending on the polymer and the formulation. And although these values can be measured using a thermomechanical analyzer (TMA), the values can vary some depending on whether one determines them in a tension or compression contact mode.

These two modes do not compress or stretch the test specimen; they only create a small tension or compressive force to ensure contact with the measurement stylus during the test. The question then becomes: Does this value change when the rubber is compressed, and does it change after relaxation at room temperature or elevated temperature and even flection response at temperature. This can be done by placing a CSR jig in an insulated chamber and measuring its CSR response as the CSR jig and specimen cool from a test temperature back to room temperature (**Fig. 25**).[8] If insulated well enough, the rate at which the temperature changes is slow enough to perform tests with reasonable temperature control.

As shown in **Fig. 26**, where both the test specimen and CSR jig were thermocoupled when running the CSR test, one can see that the CSR jig cools faster than the sample thanks to its contact with the base and the test specimen being shielded some by the CSR jig. If a hot chamber is used, one can see the values are much closer (**Fig. 27**), but it takes more time to run multiple test specimens.

Using this method allows one to evaluate the different exposure conditions, which could be an initial short exposure to a specific temperature with others done after a longer exposure, but not sufficient to result in significant aging, and then finally, after the test specimens have been aged in different fluids for longer periods of time, where more significant degradation has occurred.

This method is relatively inexpensive and can be easily set up with a normal CSR test configuration. As a general methodology, one could check these values as part of periodic CSR checks, when cooling the specimens down for normal CSR testing. Using a cool chamber might not be as accurate, but it might be good enough to provide good comparative data, to note if any significant changes in the thermal expansion response might be occurring.

In this kind of testing, it also might be good to begin to compare thermal loading constants (ΔF/ΔT) for different materials and exposures, since the values are pretty linear, and if they are determined with a standard size test specimen at the same level of strain, they should provide good comparative values to note the sensitivity of changes in the load values with respect to temperature as materials age.

Controlled temperature chamber

A limitation of the previous test configuration and test approach is that it is primarily useful for elevated temperature testing evaluations. At lower temperatures, one has an issue with materials developing a high sample stiffness value, where the stiffness ratio becomes too low to allow accurate determination of the sealing force. An alternative for this is to create a small internal chamber with a controlled temperature air feed into and out of the chamber (**Fig. 28**).[9]

Within the chamber, one can then create a free floating configuration, where the sealing force of a compressed specimen exerts, can be measured as the temperature is changed. As noted earlier, though, to get accurate representative values you need to create a thermal expansion configuration that reflects the real configuration seen in an actual sealing configuration by matching length and thermal expansion coefficients.

This test also can be done with aged samples in CSR jigs, but a special test configuration and method needs to be used. The concern with knowing the sealing force over a temperature range for a range of test configurations is to understand that seals age at elevated temperatures, but leak at low temperatures, where they lose sealing force. In some cases, people check sealing force continuously at elevated temperatures, because they may get higher sealing force values and slower loss in sealing force to try to suggest better capability. But if one does not test those same sealing configurations down to lower temperatures, the results will not be relevant to performance in real world situations.

In real world automotive applications, sealing configurations get exposed to a range of temperatures at different times of the year. When an engine is running, it gets hot, and when the engine is turned off, it cools down to the ambient temperature. So knowing how this response varies with configurations and how it changes with time and fluid exposure provides an insight as to when sealing force will be lost at what aged time and temperature.

Measurement with a profile seal

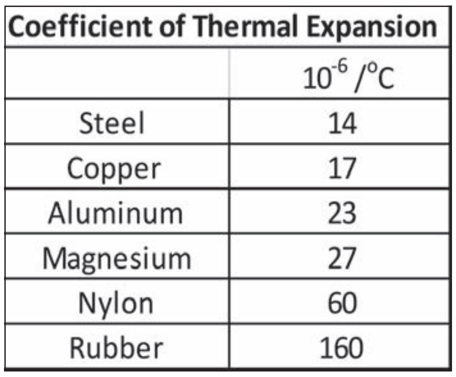
Fig. 29 shows some tests where the sealing force was checked on an actual profile seal at different percent compressions without aging.

The temperature where the sealing force was lost varied with the percent compression tested. When most people talk about the low temperature capability of an elastomer, they usually note the Tg or TR10 of the material, and often note sealing capability down to 10°C below these values. What they fail to note is that these materials and their ability to seal at low temperature also varies with percent compression, as shown with these results, and that the normal guidelines for sealing capability are good for only their initial installation and not an aged condition.

Some have suggested that sealing force is not a critical parameter, and what should be of a primary concern is when leakage occurs. So in this test, not only was the sealing force measured, but the flow rate of air in the internal cavity of the test configuration was set up at constant pressure to note leakage. What was seen was that leakage occurred at low temperature when the effective sealing force became zero.

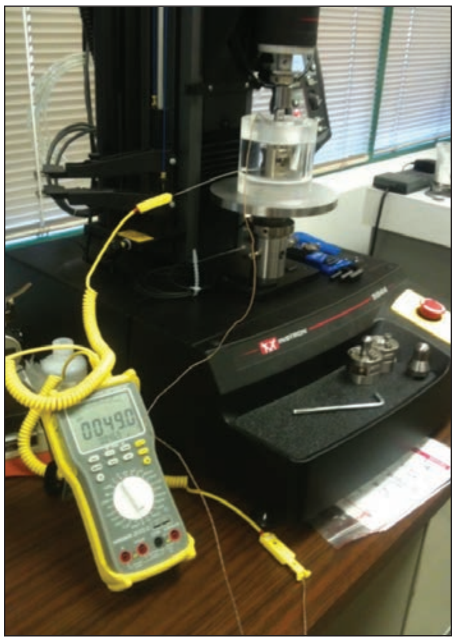
When a fluid pressure is exerted in the

Fig. 24: Typical coefficient of thermal expansion (CTE) Values for different materials.



Coefficient of Thermal Expansion	
	10^{-6} /°C
Steel	14
Copper	17
Aluminum	23
Magnesium	27
Nylon	60
Rubber	160

Fig. 25: Simple temperature chamber.



internal cavity of the test configuration, you not only exert a lateral force to test for leakage, but an axial force against the top shim, which is used to measure the sealing force. So the total force being measured is the fluid pressure (F/A) times the projected area, plus the force exerted by the seal. To measure the effective sealing force, you need to subtract the force generated by the fluid from the total measured force to get the "effective sealing force."

When this is done at different pressures, the total force changes, but the effective sealing force stays the same. This suggests that for a reasonable pressure range at low temperature, fluid pressure does not have a significant effect on the sealing response.

Design integration

In this particular application, which was an air intake manifold seal, there was a configuration similar to that shown in **Fig. 30**.

This configuration was used to perform a simple FEA structural evaluation, where a particular force was projected vertically in the sealing groove, to note the deformation of the manifold flange, with the bolt hole locations set as fixed positions with no deformation. When this was done, there were certain portions of the flange that deformed much more than others. What was surmised as happening was that initially a seal was installed in the flange which was then bolted down. When the engine heated up, differential thermal expansion occurred, with the seal exerting an increasing force at elevated temperature. At the higher temperature and higher loads, the outboard portions of the flange, which were assumed to be glass filled nylon, exhibited the most deformation, and then some creep (unrecoverable strain), where upon cooling, these areas did not return to its original position.

This resulted in less than the original design percentage compression of the seal. If the amount of creep was great enough, it would result in much lower percentage compression and leakage at a temperature higher than was expected by the particular materials and the design.

So the ability to measure the sealing force over a full temperature range can be useful, in that over the elevated temperature range, one can estimate the vertical force being exerted by the seal on the flange, which might be of concern related to flexural loads, which could result in deformations and creep, and then at a low temperatures, to see how much sealing force might be lost under different configurations and after different times and kinds of fluid exposure.

Conclusion

This paper is not intended to provide a complete approach to sealing, but aims to contribute valuable information to the process of understanding that sealing capability is not just a material response, but one that also depends on the sealing configuration.

It is an attempt to try to delineate the difference between material properties and configuration effects, and how different approaches could be used to characterize those differences. It also attempts to suggest that the ability to seal at low temperature varies with specific configurations and changes as the materials age.

It also tried to suggest that, while sealing force changes over a full temperature range as it ages, its ability to seal at low temperature decreases with this same change.

The objective overall is to suggest test approaches that could be integrated with current testing to allow the optimization of designs based on sealing force retention, and then to be able to age test specimens in a way that can allow good predictions of when leakage might occur, and in the end show that those predictions can be validated with real world durability tests. More work needs to be done in this area, and this is only a beginning intended to stir discussion and feedback.

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Fig. 26: Sealing force at temp—cool chamber—thermocoupled specimen and CSR jig.

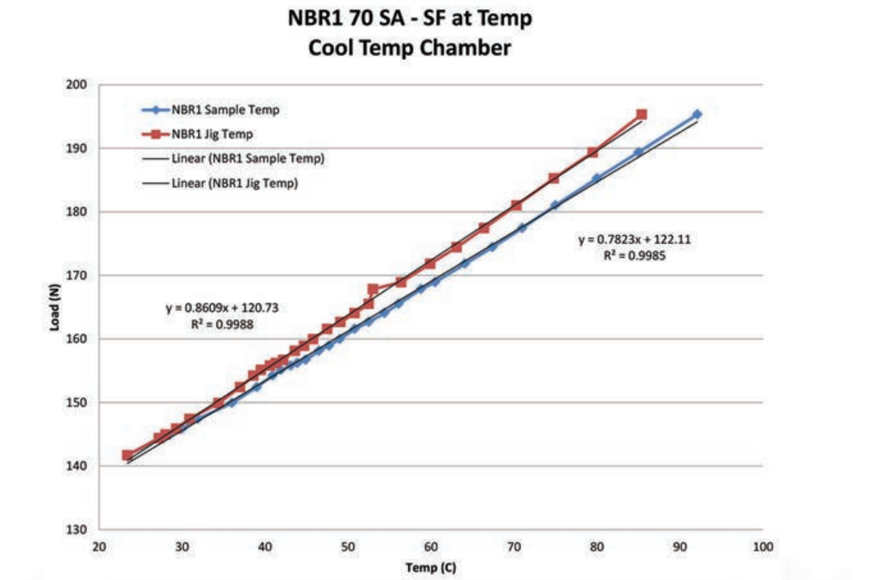

Fig. 27: Sealing force at temp—hot chamber—thermocoupled specimen and CSR jig.

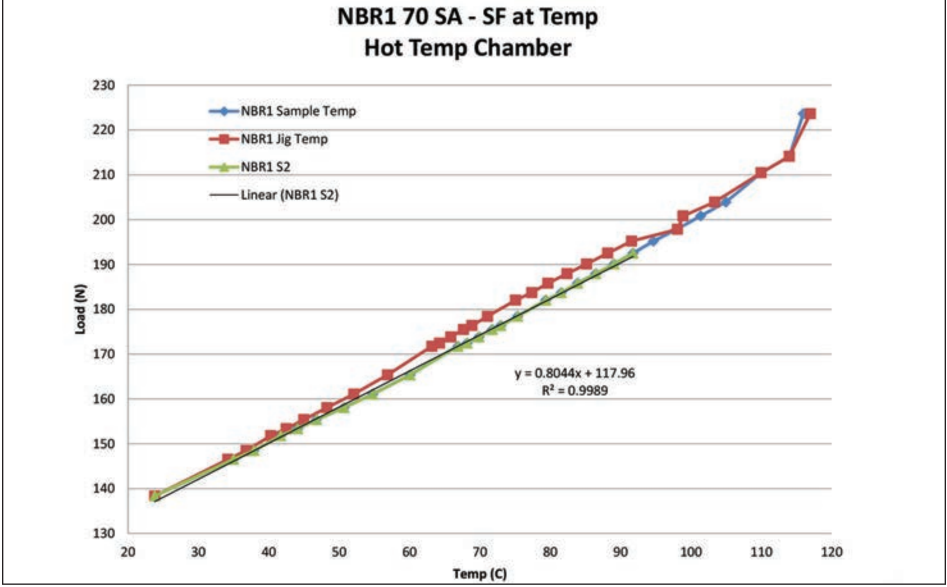

Fig. 28: Temperature controlled sealing force measurement test chamber.

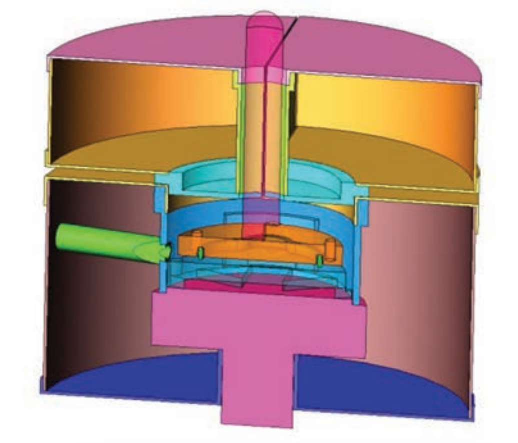

Fig. 29: Sealing force and leakage at low temperature.

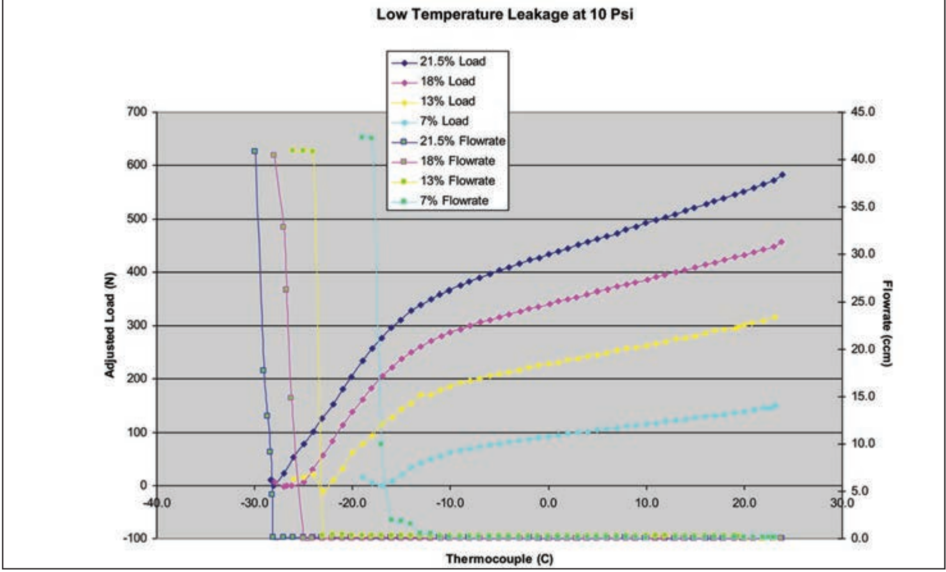

Fig. 30: Deformation under sealing load with defined fixed bolt positions.