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Calculation of O-Ring Failure Due to Material Aging

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Abstract

Applications where o-rings are used to isolate atmospheric environments within a structure are critical to weapon reliability. Failure occurs when gasses are able to travel from one side of the o-ring to the other. The anticipated cause of failure is the relaxation of the rubber over decades, the reduction in closure force, and the o-ring's consequent inability to offer a barrier to gas transport. A predictive model with tractable complexity has been developed to predict the time over which an o-ring is able to maintain an acceptable value of closure force.

Introduction.

Applications where o-rings are used to isolate atmospheric environments within a structure are critical to weapon reliability. Failure occurs when gasses are able to travel from one side of the o-ring to the other. The anticipated cause of failure is the relaxation of the rubber over decades, the reduction in closure force, and the o-ring's consequent inability to offer a barrier to gas transport. A predictive model with tractable complexity to address this problem is developed by calculating the time over which the o-ring is able to maintain an acceptable value of closure force.

The complexity of the problem derives primarily from the complexity of the stress response of the relevant (butyl) rubber. For the time scales of interest (decades), chemical processes seem to dominate the stress relaxation behavior. These processes proceed over time, and are modulated by oxygen diffusing into the o-ring material

The necessary calculation must involve the following components:

- a material model capable of predicting stress relaxation as a function of time and oxygen penetration. (This model predicts only the deviatoric stress since the material is nearly incompressible.)
- a diffusion model to predict the penetration of oxygen and other chemically active gasses into the rubber.
- a finite-element code exploiting the above constitutive model to calculate closure force. Besides the ability to accommodate the constitutive model, other necessary and special requirements of the finite element code include the ability to accommodate incompressibility, coupling with the code that does the diffusion calculation, and the ability to calculate continuously the rubber-metal interface.

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DISCLAIMER

All components of this problem are difficult but the most immature technology is the constitutive modeling of the o-ring material. It is that aspect that is discussed in the following.

Constitutive Modeling

Experimental data collected over the years indicates that the stress response of carbon-filled butyl rubber is reasonably represented as the sum of a short term stress response due to physical reorganizations and a longer term stress response due to the continuous forming and scission of crosslinks. In our aging studies, the second class (long term) of stress response seems to dominate and is outlined briefly below.

As is conventionally done, we assume that the current stress is due to the contributions of all past strains weighted by the number crosslinks formed in those states that survive to the present time:

$$\frac{\sigma_\infty(t)}{kT} = \int_{-\infty}^{t} 2\mu(t,s)[\varepsilon(t)-\varepsilon(s)]ds \qquad \text{(EQ 1)}$$

where

$\sigma_\infty(t)$	is the deviatoric part of the stress equilibrium stress
k	is Boltzman's constant
T	is absolute temperature
$\varepsilon(t)$	is the (small) deviatoric part of the strain tensor at time t
$\mu(t,s)ds$	is the population (per unit volume) of cross links formed in the time interval $(s, s+ds)$ that have survived to time t

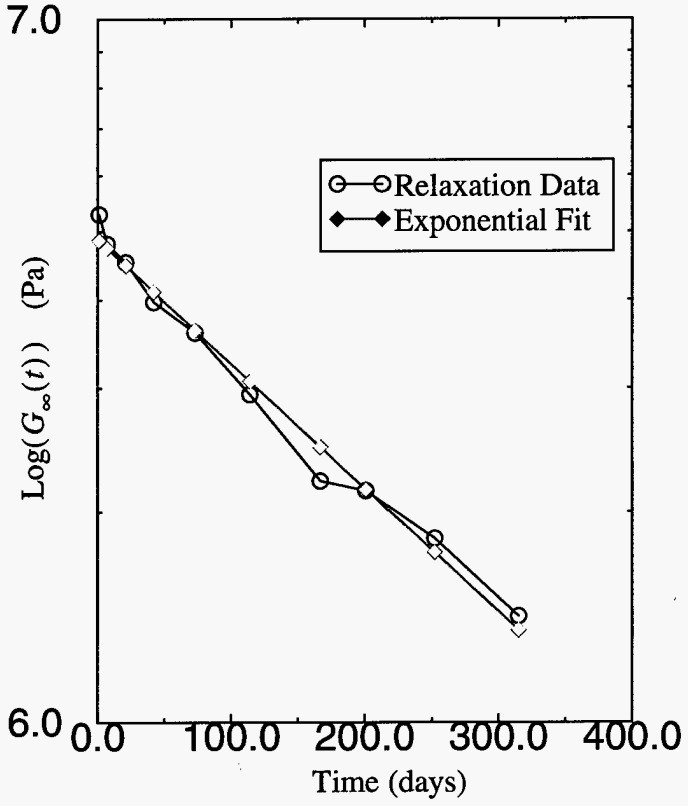
We now relate the quantity $\mu(t,s)$ to the cross link kinetics: the rate per unit volume at which crosslinks are destroyed, and the rate per unit volume at which crosslinks are formed. Further, we transform our constitutive equation into a differential form employing these quantities.

Assuming a first order evolution in crosslink population and assuming that creation and scission rates are always equal, one derives

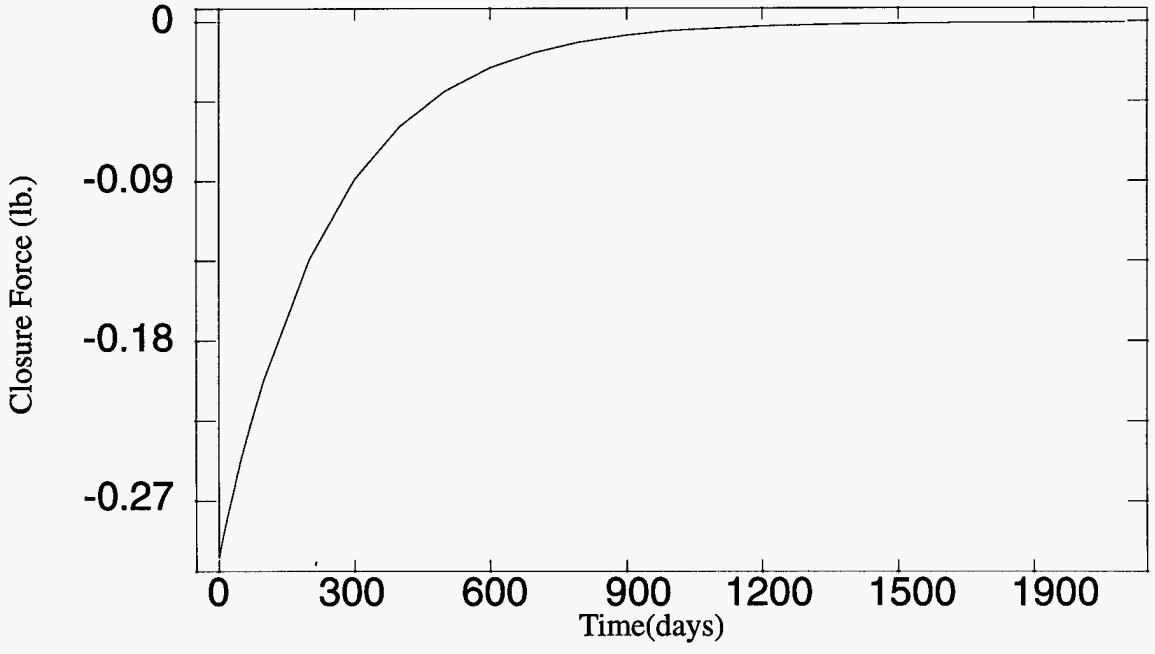
$$\frac{\partial}{\partial t}\left(\frac{\sigma_\infty}{kT}\right)+\left(\frac{\sigma_\infty}{kT}\right)\Big/\tau_\sigma(t) = 2\dot{\varepsilon}\frac{G_\infty(0)}{kT} \qquad \text{(EQ 2)}$$

The decay time, τ_σ, is itself parameterized by temperature and chemistry, and is found experimentally. That the above formulation works fairly well at fixed temperature and oxygen concentration is evidenced by the following recent data of Ken Gillen when τ_σ is selected to be

246 days. The chemical changes appear to be Arrheneius processes, so the time constant τ_σ will decrease linearly with absolute temperature according to an activation energy (~19KCal).



Finite element calculations for closure force are evidenced by the following plot. These calculations at elevated temperature (80°C) are suitable for comparison with practical laboratory tests.



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