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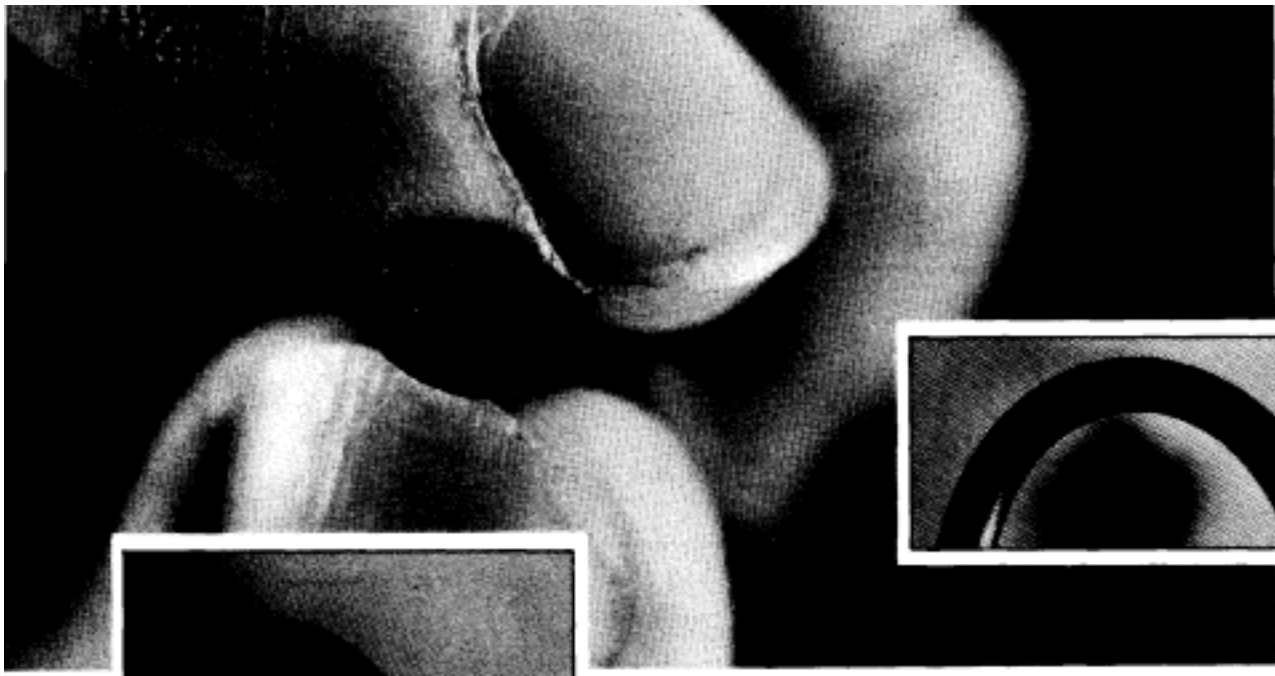
April 9, 1981

THE HIDDEN CAUSE OF SEAL FAILURE



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Blisters and internal cracks indicate that a seal is interacting with a fluid. Such failures, which are evident only upon close examination of the seal, are caused by fluid permeating into, and expanding microscopic voids in the elastomer.

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SEAL materials normally are chosen on the basis of chemical compatibility with the fluid being transferred. But even if a seal and fluid are chemically compatible, they can still interact physically, leading to leakage.

Failure results from the fluid literally burrowing into the seal and bursting it from the inside.

The reaction produces blisters or cracks in the seal that eventually provide a path for fluid leakage. This problem is especially acute at high temperatures and high pressures, but it can show up even under less severe operating conditions.

Work with seals for geothermal wells has provided insight on how to recognize failures caused by fluid/seal interaction. This research has also provided some guidance on how to avoid the problem.

How trouble starts

Fluids interact with seals because no seal material is 100% dense. Typically, molecular voids or air spaces make up about 3% of a seal's volume at

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If a seal leaks for no apparent reason, or shows cracks and blisters, it could be reacting with the fluid it's sealing. This problem is especially severe if the fluid has a molecular structure similar to that of the seal elastomer. Here's how to recognize if fluid interaction is the cause of seal failure, and how to avoid the problem.

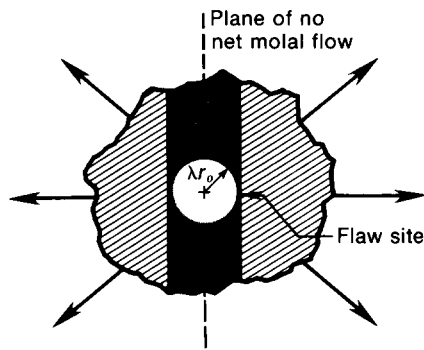


Fig. 1—Flaw site in plane of no net molal flow. Flaws, 40 μm or less in diameter, occur naturally in most elastomers. Cracks can propagate from these voids when an equilibrium shift generates a high internal pressure.

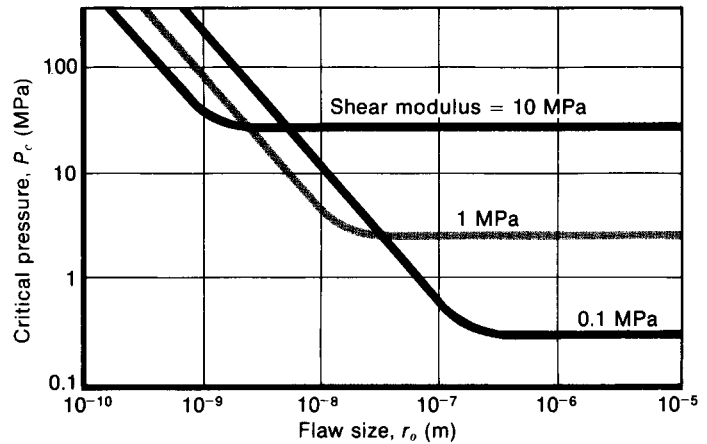


Fig. 2—Relationship between shear modulus, critical pressure, and flaw size. These variables are the primary factors controlling a seal's resistance to blistering and rupture. Because critical pressure and flaw size cannot be altered easily, the most effective way to avoid failure is to use a material with a high shear modulus.

its glass-transition temperature, Fig. 1.

Under pressure, fluid diffuses into these voids and reaches an equilibrium state at a location called the plane of no net molal flow. Any change in equilibrium creates a positive internal pressure in the voids. If the pressure exceeds a critical pressure, P_c , the voids expand, forming a blister or rupture.

Blistering is characteristic of highly elastic materials used to seal supersaturated gases and having the following physical properties.

- Low durometer (low shear modulus).
- Low crosslink density.
- High elongation (>200%).

The critical pressure for blistering is

$$P_c = \frac{5E}{6}$$

where E = Young's modulus, MPa. Blisters usually appear as small bubbles or "scales" on the seal surface.

Rupture or fracture is characteristic of linear elastic materials

having the following properties:

- High durometer (high shear modulus).
- High crosslink density.
- Low elongation (< 100%).

Critical pressure for rupturing is

$$P_c = \frac{4\lambda_b\sigma_b}{3}$$

where λ_b = extension ratio at break, and σ_b = stress at break, MPa. Rupture appears as deep internal fissures parallel to the diffusion plane. The cracks begin at voids, and the fracture propagates at high speed until internal energy dissipates enough to arrest crack growth.

Factors controlling interaction

The amount of interaction between a seal and fluid depends on the amount of fluid diffusion into the seal. Diffusion, the net transport of material in the absence of mixing, is controlled by the molecular structure, solubility, and glass-transition temperature of the seal material.

It can result from pressure gradients, temperature gradients, external force fields, or concentration gradients.

Perhaps the most important factor controlling diffusion is the solubility of the fluid in the seal. Solubility is simply defined as the speed at which diffusion occurs and depends on the molecular similarity between the seal and fluid.

Solubility of a seal can be described by a so-called solubility parameter, δ , which is a function of three intermolecular forces,

$$\delta = \sqrt{\delta_d^2 + \delta_p^2 + \delta_s^2}$$

Dispersion forces, δ_d , are common to all matter. They are omni-directional and are the major forces holding molecules together. These forces, which increase with molecular weight, are the primary source of a material's physical properties.

Dipole forces, δ_p , also called orientation-electrostatic forces, are generated when the vector sums of the various atomic bond

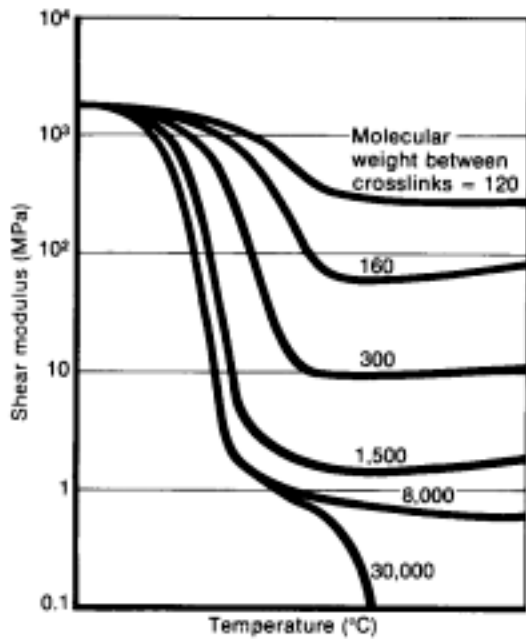


Fig. 3—How crosslinking affects shear modulus. Increasing the number of crosslinks reduces polymer-chain mobility by "tightening" the polymer structure. Thus, a highly crosslinked material has a high shear modulus and, therefore, a better resistance to blistering and rupture.

or rupture might be a problem, several steps can be taken to avoid trouble. The primary factors controlling a seal's resistance to these types of failure are critical pressure, flaw size, and shear modulus. Fig. 2 shows the relationship between these factors.

Because critical pressure and flaw size are inherent properties of a material, they cannot be changed easily. However, shear modulus, which is directly related to material hardness, can be changed by altering crosslink density or adding reinforcing fillers.

Crosslink density indicates the number of connections between the polymer chains that make up a seal. It usually is measured in terms of the average number of structural units between links. Thus, a material with a high crosslink density has few structural units between links.

Fig. 3 shows the relationship between crosslink density and shear modulus for a typical elastomer. This figure indicates that increasing crosslink density can increase shear modulus by three orders of magnitude.

The crosslink density of a material can be increased by curing it in the presence of various chemicals. This additional curing has the effect of increasing the hardness of the material without changing its molecular structure.

Table 1—Solubility of fluoropolymer elastomers

Intermolecular force ($\mu\text{J}/\text{m}^2$) ^{1/2}	FKM1	FKM2	FKM3a	FKM3b	FKM4
Dispersion force, δ_d	15.4	14.3	14.7	13.5	12.1
Dipole force, δ_p	6.6	5.1	5.7	4.7	2.9
Charge-transfer force, δ_h	9.2	7.2	8.2	6.6	3.5
Solubility, δ	19.1	16.8	17.8	15.7	12.9

Table 2—Solubility of common gases

Intermolecular force ($\mu\text{J}/\text{m}^2$) ^{1/2}	CO ₂	H ₂ S	CH ₄	N ₂	He
Dispersion force, δ_d	11.1	19.4	9.2	6.1	3.3
Dipole force, δ_p	7.2	8.2	0	0	0
Charge-transfer force, δ_h	7.2	8.2	0	0	0
Solubility, δ	15.1	22.6	9.2	6.1	3.3

angles do not cancel, thus creating a dipole. These forces are highly directional, and they act to form polymers with complex geometries.

Charge-transfer forces, δ_h , include several smaller intermolecular forces, all of which are relatively directional.

Solubility parameters can be calculated for both seal materials and fluids. Typically, a difference of four or less δ units

between the elastomer and fluid indicates a high probability of fluid solubility in the seal and the possibility of blistering or rupture failure. Tables 1 and 2 list solubility parameter values for some typical gases and fluoroelastomer seal materials.

Avoiding problems

If a check of solubility parameters indicates that blistering

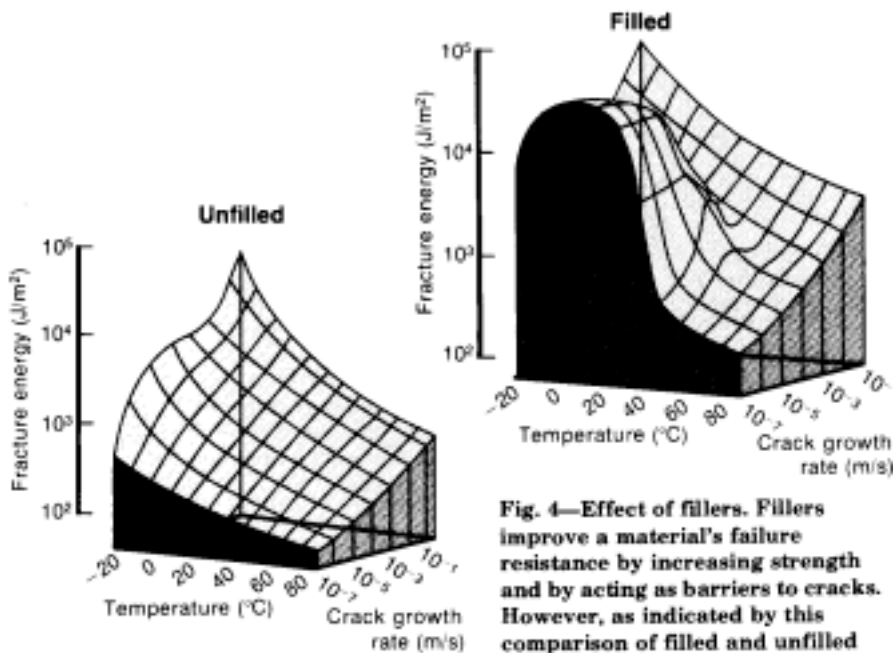


Fig. 4—Effect of fillers. Fillers improve a material's failure resistance by increasing strength and by acting as barriers to cracks. However, as indicated by this comparison of filled and unfilled SBR elastomers, fillers improve strength over only a narrow temperature range.

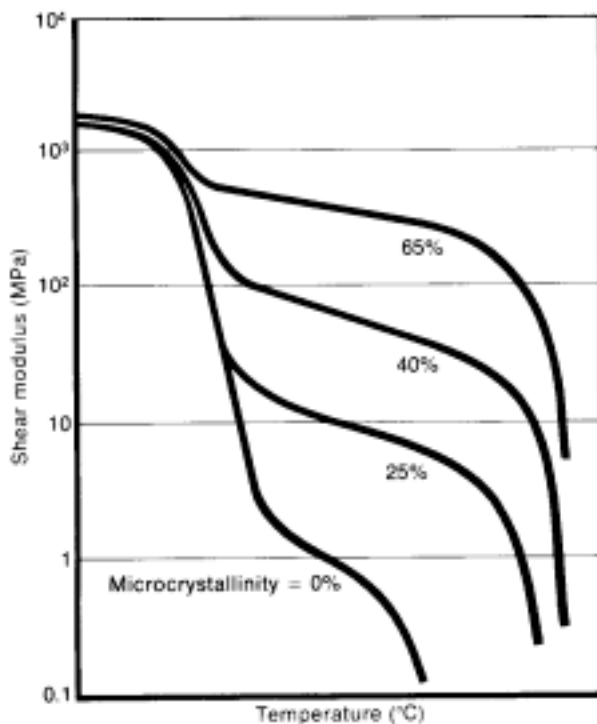


Fig. 5—Effect of crystallinity. High crystallinity increases the shear modulus of an elastomer, so that it resists blistering and rupture failure. The crystals also act like fillers to dissipate fracture energy quickly.

Fillers act as reinforcements to improve the strength of elastomers. While the exact mechanics of how fillers improve strength are not yet fully understood, the effects of filler

reinforcement can be measured. In some cases, fillers can improve strength by an order of magnitude. However, the improvement is limited to a narrow range of operating temperatures,

as shown in Fig. 4

Besides increasing elastomer strength, fillers help prevent failure by inhibiting crack growth. They act as physical barriers that deflect a crack from a straight-line path, thus dissipating fracture energy more quickly.

A more difficult way to increase shear modulus is to increase percent crystallinity, Fig. 5. Percent crystallinity is the fraction of the total polymer that is in the crystalline state. In a highly crystalline material, interchain bonds are strong, and the chains cannot slide past one another to relieve stress. In a non-crystalline (or amorphous) material, interchain bonds are weak, and the chains are free to move and rearrange themselves under stress (a process called Brownian motion).

Crystallinity can be increased with a number of processing techniques. A typical method is to heat the material and then allow it to cool slowly. In this way, the chains can arrange themselves closely as the material cools.

Another way to avoid failures from fluid/seal interactions is to use a material with a high molecular weight. In such materials, many polymer chains lie across the path of a potential crack; thus, fracture energy is dissipated quickly. However, high-molecular-weight materials are difficult and expensive to process into seal shapes.

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