

A Reconsideration of the Measurements with the O Ring Stack

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The measurements that were made in the spring of this year of Rn entry to the O ring stack were interpreted as representing diffusion through the urethane O rings in STR-96-013 ('On Rn Diffusion through Urethane and Polypropylene', 4 March 1996). This interpretation was, however, not firmly established because the derived diffusion constant $D = 2.8 \times 10^{(-7)} \text{ cm}^2/\text{sec}$ was more than an order of magnitude larger than is expected for Rn in rubbers. This led to the alternative hypothesis that Rn was mainly entering the stack by leakage through a small hole, rather than by diffusion.

This note presents a calculation of diffusion from first principles and rederives the diffusion constant for the O ring stack measurements.

A. One Dimensional Diffusion

Consider a decaying, diffusing substance in one dimensional flow along the x-axis. The concentration $C(x,t)$ satisfies the diffusion equation

$$\frac{dC}{dt} = D \frac{d^2 C}{dx^2} - \lambda C$$

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where $\lambda = 2.1 \times 10^{(-6)} / \text{sec}$ is the Rn decay constant. In the steady state $dC/dt=0$ and

$$\frac{d^2 C}{dx^2} = -\frac{\lambda}{D} C$$

which has the general solution $C(x) = A \exp(kx) + B \exp(-kx)$ where $k = \sqrt{\lambda/D}$, with A and B constants that are set by applying boundary conditions.

In the case of diffusion through a membrane of thickness d that separates two volumes in which the Rn concentrations are C1 and C2, the boundary conditions are $C(x=0) = SC1$ and $C(x=d) = SC2$, where S is the solubility of Rn in the membrane material. This leads to the general expression for the concentration

$$C(x) = S \frac{C1 \{ \exp[k(d-x)] - \exp[-k(d-x)] \} + C2 \{ \exp(kx) - \exp(-kx) \}}{\exp(kd) - \exp(-kd)} \quad (\text{eq. 1})$$

The flux F of Rn that emerges from the membrane at $x=d$ is

$$F = -D \left. \frac{dC}{dx} \right|_{x=d} = DSk \frac{2C1 - C2 \{ \exp(kd) + \exp(-kd) \}}{\exp(kd) - \exp(-kd)} \quad (\text{eq. 2})$$

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B. Application to the O Ring Stack

After assembly, the O ring stack was first evacuated and then left undisturbed for several days to establish equilibrium. Rn extractions were then made approximately every day and the number of inflowing Rn atoms was measured in a Lucas cell to be appx. 30 per hour or 1 every 120 seconds. In this mode of operation, C2 in eq. (2) is approximately zero, so this measured flux is equal to

$$DSk2C1/[exp(kd) - exp(-kd)] = 1/120/(Effective\ O\ ring\ area)\ (eq.\ 3)$$

In first approximation (see STR-96-013) the O ring stack contains 21 polyurethane O rings with 3 3/8 inch OD and 0.139 inch thickness. The groove depth and width were chosen (see drawing WPS-D-D-6102-02) to be 70% and 127%, resp., of the uncompressed thickness. With these dimensions, the compressed O ring just contacts the sides of the groove and the minimum distance through which Rn must diffuse to reach the interior of the stack is 57% of the uncompressed O ring thickness, i.e. 2.0 mm. The area of each O ring directly exposed to the outside air (and to the interior vacuum) was appx. 5.2 cm², or 110 cm² for all rings. Assuming (1) the O ring stack approximates linear diffusion through the distance d = 0.2 cm, (2) the concentration of Rn in the air outside the stack was C1 = 3 pCi/liter (equivalent to 53 Rn atoms/cm³), and (3) the solubility of Rn in polyurethane is S = 5.6, numerical solution of eq. (3) gives D = 6.3 x 10⁽⁻⁸⁾ cm²/sec.

The diffusion constant of soft polyurethane given by M Wojcik ['Measurement of radon diffusion and solubility constants in membranes', Nucl. Instr. and Meth. B61, page 8 (1991)] is 4.1 x 10⁽⁻⁸⁾ cm²/sec. Considering the possible variations in polyurethane composition, and the approximations used above, this value is in essential agreement with that determined with the O ring stack, thus adding further credence to the supposition that diffusion is the cause of Rn entry in the O ring stack.

The primary differences between this analysis and that given in STR-96-013 are (1) the solubility constant S was not included in the latter work and (2) the effective distance through which Rn must diffuse was taken here to be the minimum distance of O ring contact, rather than the uncompressed thickness of the O ring.

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