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TITLE The Effects of Exchange Gas Temperature and Pressure on the Beta-Layering Process in Solid Deuterium-Tritium Fusion Fuel

AUTHOR(S) J. K. Hoffer, L. R. Foreman, J. D. Simpson, T. R. Pattinson

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

THE EFFECTS OF EXCHANGE GAS TEMPERATURE AND PRESSURE ON THE BETA-LAYERING PROCESS IN SOLID DEUTERIUM-TRITIUM FUSION FUEL

James K. HOFFER and Larry R. FOREMAN

Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

John D. SIMPSON and Ted R. PATTINSON

KMS Fusion, Inc., Ann Arbor, Michigan 48106, USA

It has recently been shown that when solid tritium is confined in an isothermal enclosure, self-heating due to beta decay drives a net sublimation of material from thick, warmer layers to thin, cooler ones, ultimately resulting in layer thickness uniformity. We have observed this process of "beta-layering" in a 50-50 D-T mixture in both cylindrical and spherical enclosures at temperatures from 19.6 K, down to 11.6 K. The measured time constants are found to depend on the ^{3}He content as suggested by recent theoretical predictions. When using an enclosure having low thermal conductivity, the ultimate layer uniformity is found to be a strong function of the exchange gas pressure. This is due to the presence of thermal convection in the exchange gas and consequent temperature anisotropy at the solid layer surface.

1. INTRODUCTION

The concept of beta-layering was first introduced by Miller(1) in 1975. A one-dimensional theory was formalized by Martin et al.(2) in 1985. It proposed that in a chamber partially filled with deuterium and tritium (DT) fuel and cooled to below the triple point, an automatic redistribution of the solid occurs. Because of self-heating due to the absorption of beta particles, thick layers of solid DT tend to have warmer interior surfaces than do thin ones. A net sublimation of material from thick sections to thin ones takes place, expressed as

$$\delta(t) = \delta_0 \cdot e^{-t/\tau} , \qquad (1)$$

where δ_0 is the initial anisotropy in the layer thickness and the rate constant $\tau = H_s/q$, where H_s is the heat of sublimation and q is the self-heating rate. Hoffer and Foreman(3) first observed the effect in pure tritium, confirming eq. 1. Those experiments, and subsequent ones in a 50-50 mixture of DT(4), showed that the equilibration rate was also a function of the age of the material, due to the accumulation of ^{3}He in the vapor space. Recently, Bernat(5) has extended Martin's formalism to account for the diffusion of DT vapor across the interior void space in the presence of stagnant ^{3}He gas. He also arrives at Eq. 1, but with $\tau = H_s/q + \tau_3$, where

$$\tau_3 = \frac{(r \cdot d) \cdot k_s \cdot R \cdot T \cdot P_3}{d \cdot q \cdot D \cdot P \cdot (dP_{DT}/dT)} . \qquad (2)$$

In this equation, r is the inner radius of the enclosure, d is the equilibrium solid layer thickness, k_s is the thermal conductivity of the solid, R is the gas constant, T is the temperature and and P_3 the partial pressure of ^{3}He in the vapor space. D is the diffusivity of the DT-^{3}He binary gas system. P_{DT} is the vapor pressure of DT, and $P = P_{DT} + P_3$ is the total pressure. If we assume that all the ^{3}He produced by tritium decay is in the vapor space, then P_3 will increase every day by

$$dP_3/dt \approx 1.537 \cdot 10^{-4} \cdot \sigma_s \cdot R \cdot T \cdot f_s/(1-f_s), \qquad (3)$$

where, σ_s is the solid density, and f_s is the fraction of volume occupied by the solid. Using properties for DT compiled by Souers(6), we have estimated τ_3 for both cylindrical and spherical geometries, for various values of f_s as shown in Table 1. The value $f_s = 0.88$ corresponds to the case where an enclosure is filled with liquid DT and then frozen. Note that the effects of ^{3}He increase dramatically below ~16 K.

Table 1. Time Constants for Beta-Layering

T (K)	H_s/q (min)	τ_3(cyl.) (min/day) f_s=.88	τ_3(sph.) (min/day) f_s=.88	τ_3(sph.) (min/day) f_s=.2
10.0	24.74	51300	40800	18600
12.0	25.18	2740	2180	992
14.0	25.62	343	273	124
16.0	26.07	73.2	58.3	26.5
18.0	26.51	22.2	17.7	8.05
19.0	26.73	13.5	10.7	4.89
19.79	26.91	9.45	7.52	3.42

2. TEMPERATURE EFFECTS - EXPERIMENTAL PROCEDURES

We made use of the previous apparatus and optical technique(3,4), i.e., a copper cylinder sealed with sapphire windows, to insure isothermal boundaries and good optical access. To minimize the effects of ^{3}He accumulation, the DT mixture was purified in a Pd bed prior to each series of experiments. This removed the ^{3}He so well that we could fill the cylinder completely with liquid DT prior to freezing. However, it was impractical to purify the DT mixture following beta-layering at each different temperature, and thus slight accumulations of ^{3}He gas could not be prevented.

3. TEMPERATURE EFFECTS - EXPERIMENTAL RESULTS

We initially interpreted the results shown in Fig. 1 as a temperature effect in "fresh" DT (i.e., DT having no ^{3}He impurity) and we fitted the data with an Arrhenius expression. However, the Bernat model outlined above suggests a better interpretation, namely that there is virtually no effect of temperature on the rate of beta-layering in pure DT, but that the effect of ^{3}He accumulating in the vapor space is so strongly temperature dependent that even miniscule amounts of ^{3}He will dominate the rate of beta-layering below ~14 K. Figure 1 shows values of τ calculated from Eq. 2 at times corresponding to the beginning and the end of each experiment. The close agreement with our measured values shows that the model describes the physics of beta-layering in isothermal enclosures remarkably well.

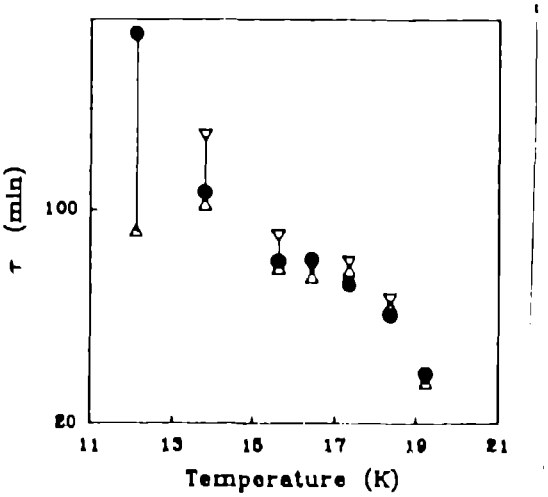

FIGURE 1
Equilibration rate constants in "fresh" DT solid at various temperatures. The horizontal bars represent values of τ predicted by Eq. 2 at the beginning and at the end of each experiment. The data are measured at different times and thus do not correlate directly with temperature.

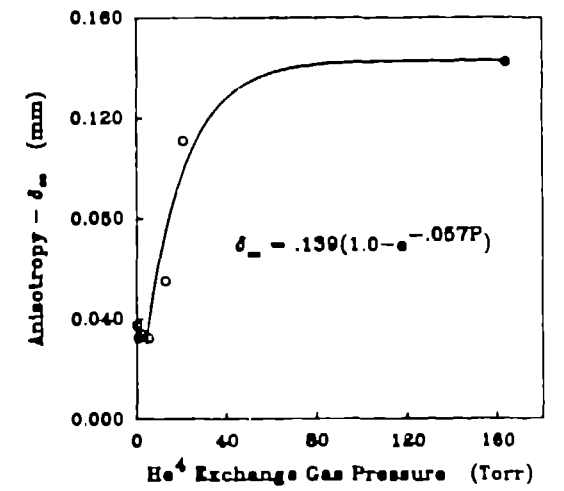

FIGURE 2
The dependence of the exchange gas pressure on the ultimate symmetry observed following beta-layering of solid DT in a spherical lexan shell.

4. PRESSURE EFFECTS - PROCEDURES AND RESULTS

In the second set of experiments, the copper cylinder was replaced by a hollow lexan sphere having the same volume. This is characteristic of prototype inertial confinement fusion (ICF) reactor targets. In both sets of experiments, the DT containers were thermally linked to the cryostat by ^{4}He gas at a pressure of ~600 torr. But, with the poorly conducting lexan sphere, a large asymmetry in the equilibrium layer thickness, δ_∞, was observed. Suspecting that this was an effect of convection in the ^{4}He exchange gas, we conducted a series of experiments at decreasing pressures until relatively symmetric layers were achieved, as shown in Fig. 2. The slight anisotropy remaining below ~5 torr is probably due to the metal fill tube and support tube attached to the poles of the sphere.

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