

ON THE ACTIVATION ENERGY
FOR POLYGONIZATION

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A concept has arisen in the literature on polygonization which we consider questionable; that is, the belief that polygonization data in the form of the growth rate of polygon walls may be used to derive a single activation energy in each of two different temperature regions.

Data amenable to this type of analysis has been reported by Gilman⁽¹⁾ on zinc. His results are reproduced in Fig. 1. In this figure, the mean orientation difference between polygon walls is plotted versus the logarithm of annealing time for various constant annealing temperatures.

Similar polygonization data has been reported by Amelinckx and Strumane⁽²⁾ on sodium chloride, Hibbard and Dunn⁽³⁾ on silicon iron, and Sinha and Beck⁽⁴⁾ on zinc. In this discussion only the data in Reference 1 is analyzed.

The procedure apparently used by Gilman for obtaining activation energies was to cut the isothermal annealing curves in Fig. 1 along a line of constant θ ($\theta = 0.01$ rad.), determine the slopes of the curves, $d\theta/dt$, at the points of intersection, plot $\log d\theta/dt$ versus the reciprocal of the absolute temperature, and then obtain the activation energy from the slope of this curve. Gilman found that there were two straight line portions meeting at a rather sharp break in the graph of $\log d\theta/dt$ versus $1/T$ and thus two activation energies, one for high temperatures and one for low temperatures.

In reference 1, the activation energies were determined for only one value of θ . It is the purpose of this paper to show that a single activation energy cannot be assigned to each temperature range because the apparent activation energy is a function of the angle θ , at which the polygon growth curves are cut.

The initial straight part of the polygon growth curves of Fig. 1

has an equation of the form

$$\theta = \theta_0 + \beta \log t \quad (1)$$

where θ is the polygon wall angle, t is the annealing time, and θ_0 and β are constants for each annealing temperature. Values of β may be obtained by selecting corresponding values of θ and t at two points on a particular growth curve, substituting these into Eq. (1) and then subtracting the two equations obtaining the result

$$\beta = \frac{\theta_2 - \theta_1}{\log t_2 / t_1} \quad (2)$$

Differentiating Eq. (1) with respect to time gives

$$d\theta/dt = \beta/t \quad (3)$$

Taking the antilog of Eq. (1), solving for t , and substituting this value into Eq. (3) yields

$$d\theta/dt = \beta \exp \left[-\frac{\theta - \theta_0}{\beta} \right] \quad (4)$$

Equation (4) illustrates the fact that, for a particular annealing temperature which determines β , the polygon growth rate is dependent on the instantaneous value of the polygon wall angle. Thus, in analyzing polygon growth curves for activation energies, the growth curves must be cut along lines of constant θ . A meaningful activation energy cannot otherwise be assigned to the polygonization process.

Using Eqs. (2) and (3) and the points of intersection along lines of constant θ , curves of $\log d\theta/dt$ versus $1/T$ may be constructed.

Applying the above procedure to the data of Gilman,⁽¹⁾ the curves

shown in Fig. 2 have been plotted for several values of θ .

Selecting corresponding values of $d\theta/dt$ and $1/T$ at two points on a line of constant θ , the activation energies may be calculated by means of the formula

$$\Delta H = \frac{k \log \dot{\theta}_2 / \dot{\theta}_1}{\left[1/T_1 - 1/T_2 \right]} \quad (5)$$

where:

$\dot{\theta} = d\theta/dt$ and k is Boltzmann's constant.

In Fig. 2 a linear plot is obtained for the two temperature regions, indicating that an Arrhenius type relationship is obeyed. At $\theta = 0.01$ rad. (the angle analyzed by Gilman), we obtained 60 and 21 kcal/mol for the activation energies of the low and high temperature regions respectively which agree with the values of 61 and 22 kcal/mol reported by Gilman.

The dependence of activation energy on polygon wall angle for zinc is illustrated in Fig. 3. In the high temperature region, ΔH is practically a linear function of θ .

(2)

Amelinckx and Strumane, in studying the kinetics of polygonization in sodium chloride, have also reported values of activation energy determined for only one value of θ . In applying the analysis presented in this paper to their data, we were unable to reproduce their results. It was learned through private correspondence with R. Strumane that values of $d\theta/dt$ were determined using the approximation $d\theta/dt = \Delta\theta/\Delta t$, where $\Delta\theta = 0.001$ radian was taken as a fixed reference growth and values of Δt necessary to reach this value of $\Delta\theta$ were read from Fig. 17 of reference 2. Using this method of calculation, we were unable to reproduce their results (Fig. 18, ref. 2) from the original data (Fig. 17, ref. 2). It appears to the writers that the data and techniques of analysis reported by Amelinckx and Strumane need some clarification.

Examination of the polygonization data reported by Hibbard and Dunn⁽³⁾ on silicon iron and Sinha and Beck⁽⁴⁾ on zinc also shows that the activation energy continually increases as the polygon wall angle increases.

In both references 1 and 2, the polygonization data has been interpreted in terms of the theory developed by Mott⁽⁵⁾ and Friedel⁽⁶⁾ (for a review see ref. 7). This theory states that polygonization will occur under saturation conditions at high temperatures with an activation energy U_L equal to the lattice self-diffusion activation energy and at lower temperatures with an activation energy equal to $U_L + U_j$, where U_j is the energy of formation of a jog on a dislocation.

The saturation condition is supposed to occur if the distance between the climbing dislocation and the sources or sinks supplying vacancies to the dislocation is larger than the average spacing of jogs on the dislocation. However, Thomson and Balluffi⁽⁸⁾ have pointed out that this condition is unrealistic, since it does not take into account the fast diffusion of defects along the dislocation to the jogs. If the theory of Mott and Friedel were correct, the activation energy for self-diffusion would have to continually increase during the polygonization process in order for the theory to agree with the experimental results in Fig. 3.

From the results of the analysis presented in this paper, we conclude that : (1) an examination of all available sets of quantitative polygonization data shows that the activation energy for the process increases as the polygon wall angle increases and (2) the polygonization theory due to Mott⁽⁵⁾ and Friedel⁽⁶⁾ is inadequate in that it does not describe the experimental results in references 1, 2, 3, and 4, nor does it account for the mechanism of fast diffusion of defects along the dislocation to the jogs.

REFERENCES

1. J. J. Gilman, *Acta Met.*, 3, 277, (1955).
2. S. Amelinckx and R. Strumane, *Acta Met.*, 8, 312,(1960).
3. W. R. Hibbard and G. G. Dunn, *Acta Met.*, 3, 409, (1955).
4. P. P. Sinha and P. A. Beck, *J. Appl. Phys.*, 32, 1222, (1961).
5. N. F. Mott, *Phys. Soc.*, 64, 729, (1951).
6. J. Friedel, *Les Dislocation* (Gauthier-Villars, Paris, 1956), p. 194.
7. S. Amelinckx and W. Dekeyser, *Solid State Physics*, 8, 452, (1959).
8. R. M. Thomson and R. W. Balluffi, to be published, *J. Appl. Phys.*, (1961).

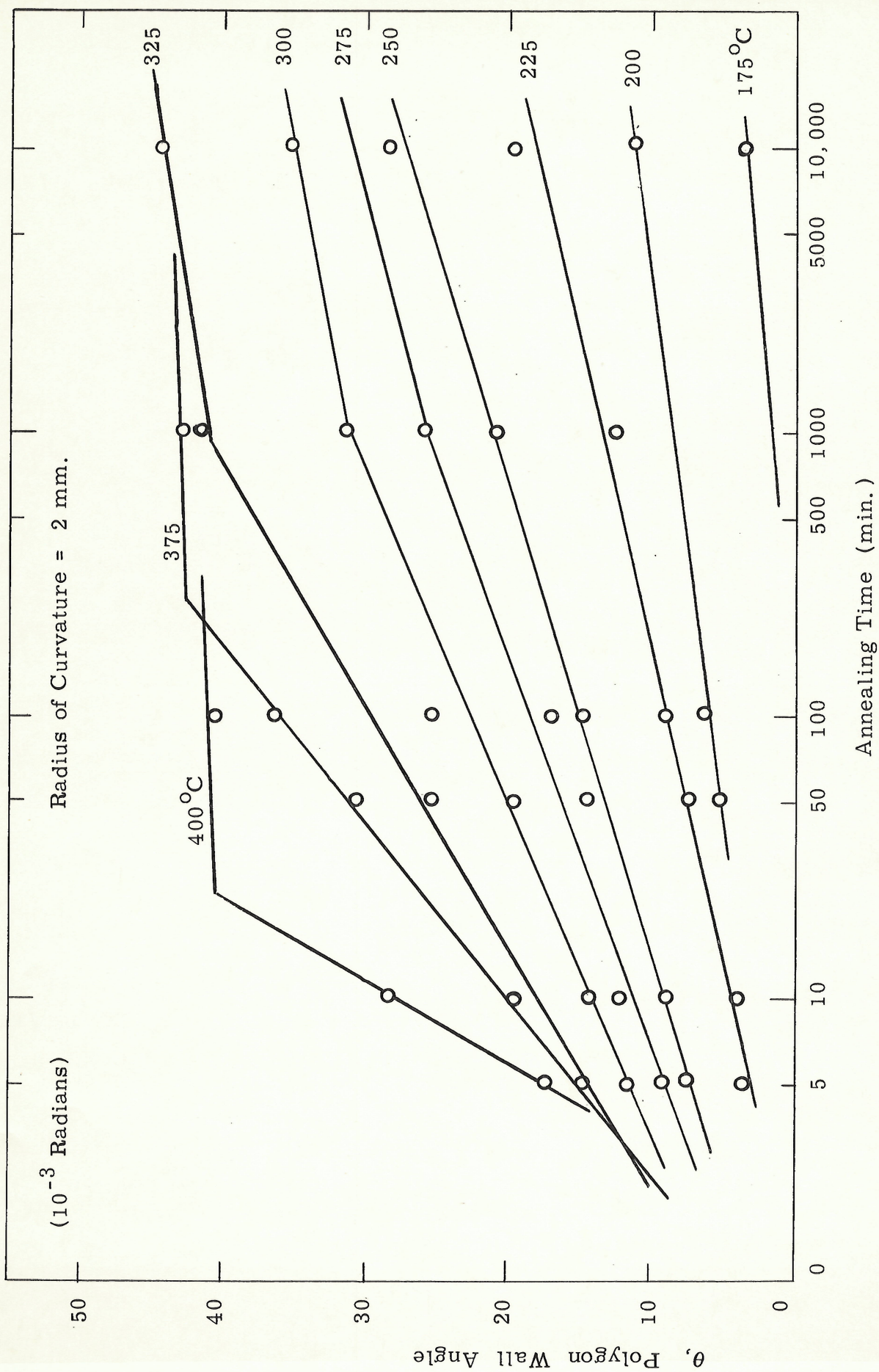


Fig. 1 - Isothermal Polygon Wall Angle Growth Curves for Zinc (after Gilman).

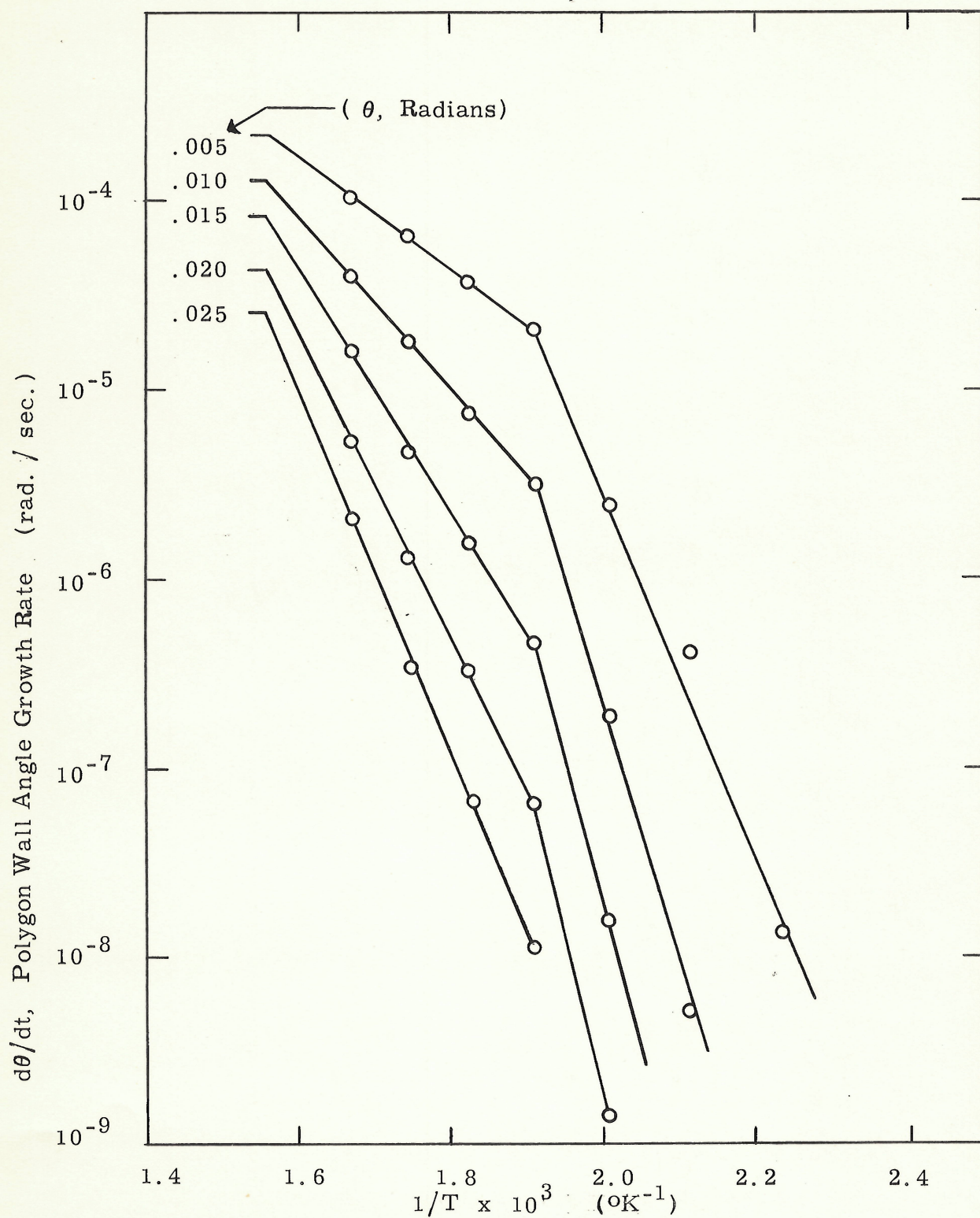


Fig. 2 - Temperature and Polygon Wall Angle Dependence of the Polygonization Rate in Zinc Crystals.

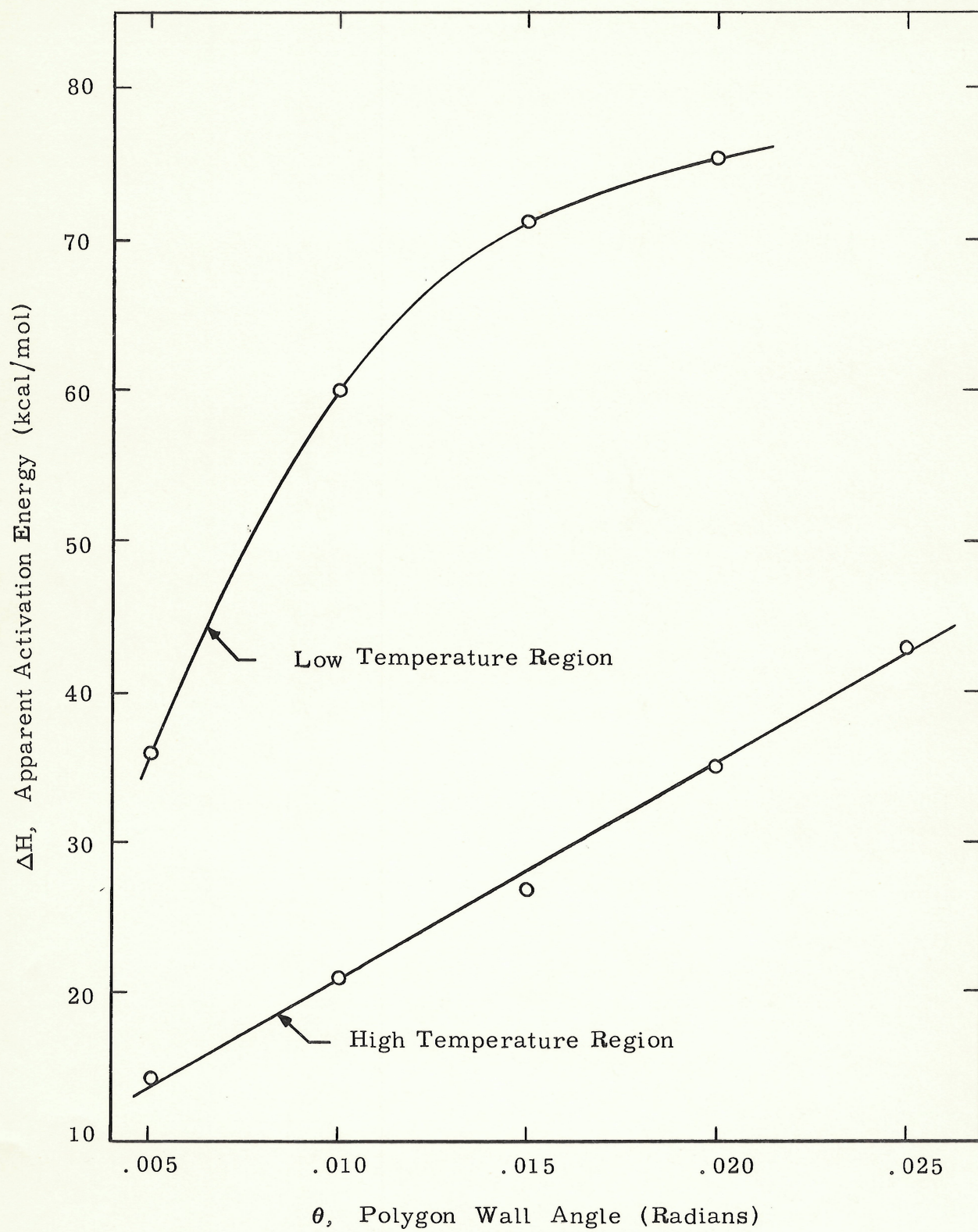


Fig. 3. - Dependence of Activation Energy on Polygon Wall Angle