

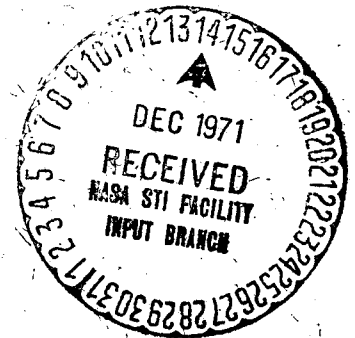
X-644-71-418
PREPRINT

NASA TM X-65765

THERMAL COEFFICIENTS OF TECHNOLOGY ASSIMILATION BY NATURAL SYSTEMS

ROBERT F. MUELLER

OCTOBER 1971



GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

N72-12338 (NASA-TM-X-65765) THERMAL COEFFICIENTS OF
TECHNOLOGY ASSIMILATION BY NATURAL SYSTEMS
R.F. Mueller (NASA) Oct. 1971 12 p
CSCL 08D

Unclas
09760

G3/13

FACILITY 11111 00100
(NASA CR OR TMX OR AD NUMBER)

(CATEGORY)

X-688-71-418

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Robert F. Mueller
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ABSTRACT

Estimates of thermal coefficients of the rates of technology assimilation processes have been made. Consideration of such processes as vegetation and soil recovery and pollution assimilation indicates that these processes proceed ten to several hundred times more slowly in Earth's cold regions than in temperate regions. It is suggested that these differential assimilation rates are important data in planning for technological expansion in Arctic regions.

THERMAL COEFFICIENTS OF TECHNOLOGY
ASSIMILATION BY NATURAL SYSTEMS

It is a well known fact that environments and biota in Earth's cold regions are "fragile" in the sense that their recovery from the impact of man's technology is slow.¹ That this is largely a temperature effect is indicated by its occurrence both in extreme latitudes and at extreme altitudes. The kinds of processes involved are predominantly biological ones such as the growth of ground cover and other vegetation, the development of soil humus and the general activities of microorganisms. Where technological wastes or debris must be disposed of both biological and purely chemical processes of decay and assimilation will be active and the degraded material will be dispersed in the surrounding environment. We refer to all such processes, whether involving recovery or chemical assimilation as "assimilative".

It has already been shown that the assimilation of technology essentially consists in a dissipation of energy which is borne by all known environmental pollutants.² Because the assimilation processes are predominantly chemical in nature they may be characterized in terms of chemical kinetic parameters and so should possess definite coefficients which are functions of the temperature. Although the technological activity is generally designed to occur in definite "machine temperatures" the assimilation of wasted and utilizable energy and the resultant pollutants as well as the recovery processes generally occur at the ambient temperatures of the environment. It is interesting that these considerations, which are so important in the terrestrial environment apply equally to any proposed quasipermanent stations on other planets.

We must however distinguish the effect of temperature from a number of other factors which also influence the rates of the assimilative processes. For example it is well known that in the case of forest trees the growth rate depends on such factors as soil nutrients, light exposure, drainage and soil moisture.³ The latter factor is particularly important in governing the development of soil and vegetation types and along with temperature enters critically into controlling rates of rock weathering.⁴ Indeed it appears that many chemical and biochemical processes in arid regions are governed more by soil moisture than by temperature.⁵ It is likely that this factor also plays a critical role in many other natural assimilative processes. Thus in many climatic regions the attribution of technology assimilation rates to temperature effects will be ambiguous. However, if we confine ourselves to the discussion of regions in which the water table normally intersects the surface and which show fairly continuous vegetative ground cover much of this ambiguity will be avoided. In any case we shall here consider only those gross thermal effects which are likely to be apparent over a considerable temperature range.

The rates of chemical reactions, whether they be biochemical or purely chemical in nature, may be discussed in terms of the theory of absolute reaction rates.⁶ According to this theory the rate constant K takes the following form:

$$K = \nu \frac{kT}{h} \exp(\Delta S^*/R) \exp(-\Delta H^*/RT), \quad (1)$$

in which the various quantities are defined as follows:

ν transmission coefficient

k Boltzmann's constant

- h Planck's constant
- T the temperature in °Kelvin
- ΔS^* the entropy of activation
- ΔH^* the enthalpy of activation
- R the gas constant

For our purposes the factor $\exp(-\Delta H^*/RT)$ is of greatest interest since the temperature coefficient of the rate constant is expressed through ΔH^* and the closely related experimental energy of activation E^* . Thus under the low pressure conditions of Earth's surface environment we have

$$\frac{\partial \ln K}{\partial T} = \frac{E^*}{RT^2}, \quad (2)$$

where

$$E^* = RT + \Delta H^* .$$

Most biochemical reactions proceed through enzyme catalysis. If the overall reaction consists of a number of steps it is likely that the overall rate will be governed by the slowest of these steps. Although it is unlikely that simple sequences of reactions generally characterize complex biochemical processes⁷ it has been inferred that an effect as complex as the rate of walking in ants is governed by the rate of hydrolysis of ATP.⁸ Since both the rate of hydrolysis of ATP and the walking rate of ants were found to have activation energies of 25 K cal/mole between 8° and 16°C and 12 K cal/mole between 16° and 30°C this appears to be a reasonable inference.

Although complex processes may at times be characterized by well defined activation energies and temperature coefficients, the assimilation of technology

and its wastes in general involves a multitude of such processes. Thus in all probability the net effect of temperature on a process such as sewage assimilation will not be describable by a single activation energy. However recent work indicates that relatively complex elements of this process may be characterized by kinetic parameters. Thus it was found⁹ that the rates of phosphorous deposition, nitrification and the nitrogen utilization by algae could be described by first or second order rate equations, depending on the reaction. The same data imply energies of activation between 14 and 20 K cal/mole for these reactions.

The upper temperature limits of biological processes are generally quite well defined because they tend to be governed by such reactions as the denaturation of proteins, and these reactions have high activation energies.^{7,8} Consequently these reactions have large temperature coefficients and sharp cut-off temperatures. By contrast the activation of enzyme catalyzed reactions which are operative in the normal and low temperature range of organic activity tend to have low activation energies precisely because they are enzyme catalyzed. As suggested by Eyring, Lumry and Spikes¹⁰ the activation energies of these reactions are usually not much more than 20 K cal/mole. Also Daniels and Alberty¹¹ have emphasized that many chemical reactions double or triple their rates with each 10°C increase in the temperature. At room temperature these temperature coefficients correspond to activation energies of approximately 10 and 20 K cal/mole respectively. Consequently it seems safe to infer that most biochemical and chemical assimilative processes will fall in this range of activation energies.

We may illustrate the effect of a decrease in temperature on the time scales of typical chemical or biochemical reactions with activation energies of 10 to

20 kilocalories per mole. It is interesting to compare the rates of such reactions at temperatures corresponding to Earth's climatic zones. Thus it has been found¹² that the mean surface air temperature of the northern hemisphere at latitude 30°N is 21°C, while the corresponding temperatures 60°N and 80°N are -1°C and -17°C respectively. In degrees Kelvin these temperatures are 294°, 272° and 256°K. If we first assume that $E^* = 10$ K cal/mole we may compare the effect of an increase in latitude from 30° to 60°N by integrating equation (2). We then obtain

$$\log \frac{K(294)}{K(272)} = \frac{10,000}{4.576} \left(\frac{1}{272} - \frac{1}{294} \right),$$

where base ten logs have been used. Consequently $\frac{K(294)}{M(272)} \simeq 4$. Thus the change in mean temperature from 21 to -1°C corresponds to increasing the time scale of the reaction by a factor of 4. If on the other hand we assume that $E^* = 20$ K cal/mole we obtain

$$\frac{K(294)}{K(272)} \simeq 17.$$

Furthermore the increase in the reaction time scale with a further decrease in the temperature, corresponding to the 80°N climatic zone is even more pronounced. Thus if we again assume that $E^* = 20$ K cal/mole we have

$$\frac{K(294)}{K(256)} \simeq 170$$

Obviously greater activation energies will result in even larger times of reaction.

Our use of mean temperature corresponding to latitudes is for illustrative purposes only. For a realistic assessment of the time scales of technology

assimilation in any geographic region the details of climate and the nature of the process must be taken into account. Most chemical processes will increase in rate with the temperature and be most active in the summer season. In cold climates most processes will be at a virtual standstill in the winter season. Furthermore, the reaction rates will generally vary continuously between these extremes. Thus a comparison of two geographic regions involves available reaction times as well as the temperative dependence of rate constants.

If C_i is the concentration of a reacting constituent i its rate of disappearance will be given by the general functional relation

$$\frac{dC_i}{dt} = -Kf(C_i, C_j, \dots), \quad (3)$$

where K is the conventional rate constant, f is a generalized concentration function and C_j represents the concentration of reactants other than i . K is a function of the temperature, and the temperature varies as a function of the time. Then if we assume the C_j 's may be expressed in terms of C_i integration of (3) yields

$$F(C_i) = \int K(t)dt, \quad (4)$$

Where F is another function and the integral represents the seasonal cycle of activity.

In order to avoid the complication of equation (4) in which reaction times are mixed up with temperatures we define an "effective temperature" of technology assimilation T' for each climatic region and reaction. Thus for (4) we obtain

$$\int K(t)dt = K'\Delta t'. \quad (5)$$

For the particularly simple case in which a reaction proceeds at a constant rate in the active season we have

$$\frac{K'}{\Delta t} = \frac{K}{\Delta t'} \quad \text{with} \quad \begin{array}{l} T \geq T' \\ K \geq K' \\ \Delta t' \geq \Delta t \end{array}$$

Thus while the effective temperature is less than the reaction temperature, the effective reaction time is greater than the true reaction time. Obviously K and K' and Δt and $\Delta t'$ diverge as climates become more extreme and converge for moderate climates. It is possible that effective temperatures might be defined for a complex process as well as for its constituent chemical reactions through observation of rates and their temperature dependencies.

It is important to note that the kinetic processes as discussed above represent only the minimal requirements for technology assimilation from the standpoint of the long term viability of communities. Even after the initial assimilative process has occurred there remain residual problems of technological impact. Examples of such problems are the loss of topsoil, the secular accumulation of carbon dioxide in the atmosphere and the extinction of organisms. The resolution of these residual problems also has a kinetic aspect. For example top soil can be rebuilt after hundreds or thousands of years and CO_2 will eventually be absorbed by the oceans and lithosphere.¹³ However the time scales of these processes are so great that they fall into a different category of phenomena than those under discussion.

While the temperature dependencies of most technology assimilative processes are as yet unknown it seems clear from consideration of the component

chemical reaction and existing observational data that these are likely to be significant. Consequently the possible detrimental impact of technological development in high latitudes or other cold regions needs to be carefully evaluated. For example if the foregoing general estimates of the variation of reaction rates with temperature are even approximately correct it would seem that the pace of technological development in much of the state of Alaska and in other cold regions should be slowed by a factor of ten to several hundreds as compared with the pace of development of the forty-eight contiguous states. Indeed that this conclusion may actually be conservative is indicated by the fact that only air temperatures were discussed while many assimilative reactions must occur in soil, subsoil or water which have lower mean or warm season temperatures. Also it is clear that even within the forty-eight contiguous States and in other developed temperate regions, where technology assimilation is favored by higher temperatures, the build-up of pollutants indicates that the burden of technology is already too heavy for the natural systems to maintain.

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