The harsh truth about terraforming

I enjoyed reading Charles Day's column on the subject of terraforming in the July 2021 issue of PHYSICS TODAY (page 8). I was only a year old in 1942, so I missed seeing Jack Williamson's story that introduced the term when it was published. I also missed it in the mid 1950s when I read many of the back issues of *Astounding Science-Fiction*.

My first introduction to the concept was from reading *Sands of Mars* by Arthur C. Clarke, first published in 1951, although I don't believe he actually used the term "terraforming." He describes selectively breeding native plants that extract oxygen from the Martian soil to release it into the atmosphere—a precursor of the biological approach in Kim Stanley Robinson's Mars trilogy—and turning Phobos into a second sun to warm the planet.

On a more serious note, it seems to me that the very concept of terraforming represents a striking display of human hubris. Today we are struggling to safeguard the health of Earth's critical ecosystems from the unintended consequences of the artificial environment we have built. Given our limited success so far and significant chance of failure, the idea that we could create a viable, self-sustaining environment on another planet anytime soon seems pretty far-fetched. The reality is that a planetary ecosystem is many orders of magnitude more complex than what we are currently able to deal with. The time will likely come when our capabilities will have reached that level, but for the moment, terraforming appears destined to remain in the realm of science fiction and, apparently, board games.

MARS'S SURFACE as captured by NASA's *Curiosity* rover. The image's white balance has been adjusted to show how the surface of Mars would look under Earth's skylight. Terraforming Mars has been the subject of several works of science fiction, such as *Sands of Mars* by Arthur C. Clarke. (Courtesy of NASA/JPL-Caltech/MSSS.)

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More on Arrhenius plots

Axel Lorke's Quick Study in the May 2021 issue of PHYSICS TODAY (page 66) describes Svante Arrhenius's illustrious career and provides important insight into Arrhenius's quantitative description of thermally induced processes. Lorke describes the broad power of the famous Arrhenius relationship $a = A\exp(-E_a/k_BT)$, where k_B is the Boltzmann constant and T is absolute temperature, to capture complex physics with temperature-dependent measurements aimed at the extraction of a single parameter, the activation energy E_a. Presenting an example from thermodynamics and another from kinetics, he shows how E_a connects closely to independently determined quantities such as a semiconductor's bandgap energy and the UV-induced gelation energy of proteins.

The Quick Study focuses on the slope of logarithmic plots of rates and other temperature-dependent quantities versus inverse temperature $1/T$. In kinetics, the prefactor A of the exponential also provides important physical information. It may be obtained by extrapolating an Arrhenius line like that of figure 3 in Lorke's Quick Study to yield an intercept at the

$1/k_B T = 0$ axis. If the quantity measured is the frequency of a process, as is often the case in solid-state physics, the prefactor A can be called the attempt frequency, with A^{-1} being the limiting time required to surmount the activation barrier as the temperature approaches infinity. In textbook examples, for small E_a, this approach yields plausible values for such frequencies. Further, if the E_a of such a process is modified only slightly, the intercept does not change.

Starting with reports by Frederick Hurn Constable[1] in 1925 and by Wilfried Meyer and Hans Neldel[2] in 1937, researchers have done a great number of experiments on sets of closely related materials and systems in which the prefactor of Arrhenius plots of a related set varies systematically with E_a. While care must be taken to avoid artifacts, it has been clear for some time that the phenomenon is real.[3] For a wide-ranging variety of sets of related physical, geological, biological, and chemical phenomena, the logarithms of those intercepts vary linearly with E_a. That also means the Arrhenius fit lines cross at an isokinetic temperature at which the rate is independent of E_a. Those observations have various names: the isokinetic rule, the compensation law (because the increase in the prefactor partially compensates for the increase in E_a), and the Meyer–Neldel rule.

The meaning and explanation of the Meyer–Neldel rule were long considered to be a mystery, but work by a number of groups in the final decades of the past millennium provided a clear theoretical framework for both kinetic and equilibrium systems. The key to activation is not the energy or enthalpy; it is the free-energy change, which includes an entropy term. When the activation barrier is large, the entropy change increases with E_a, and that increases A.

In 2006 one of us (Yelon) coauthored a review of the state of the art in experiment and theory,[4] which have continued to evolve since. Systematic studies yield information concerning the characteristic energy of the collective excitations—phonons or local vibrations—that are aggregated to surmount the activation barrier.[5] In some cases, notably studies of electronic or ionic conductivity, important information concerning mechanisms can be obtained. Like the Arrhenius relation that spawned it, the Meyer–Neldel rule is an elegant way to gain insight into the fundamental interactions governing temperature-dependent processes.

References

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Axel Lorke's Quick Study (PHYSICS TODAY, May 2021, page 66) discusses underlying connections be-