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ADVANCES

MATERIALS SCIENCE

Elemental Urgency

Most metals currently
lack substitutes

Half a century ago only a handful of materials were in widespread use for consumer and industrial products—wood, iron and brick, to name a few of the most prominent ones. Today a single computer chip contains more than 60 elements, ranging from tungsten to ytterbium. Contemporary technology's reliance on such diverse resources, particularly metals, piqued the interest of Thomas Graedel, an environmental scien-

tist at Yale University. With increasing demand for these elements, are replacements available if a shortage occurs?

In most cases, no. In fact, strong substitutes exist for none of the examined 62 metals or metalloids on the periodic table in all their uses, Graedel and his colleagues found after a comprehensive analysis of the elements' properties, life cycles and applications. And inadequate or nonexistent alternatives plagued a dozen metals when it came to their major uses. Replacements in these cases invariably would lead to degraded performance.

There may be a silver lining to situational scarcities, however, Graedel says. They should inspire engineers to design completely novel, transformative materials.

—Jennifer Hackett

The Periodic Table of Substitute Availability

LITHIUM (Li) Although in high demand, lithium has strong stand-ins for most of its major uses. For example, lithium-based batteries can be replaced with nickel-metal hydride or zinc-based alternatives with little performance loss.																COPPER (Cu) Aluminum can be used in place of copper, but it performs poorly as an understudy in the electrical conductor's most widespread roles—in industrial wire and electronics components such as transistors.																	
H																																	He
Li	Be																	B	C	N	O	F	Ne										
Na	Mg																	Al	Si	P	S	Cl	Ar										
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr																
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe																
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn																
Fr	Ra	†	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo																
*Lanthanides			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu																
†Actinides			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr																

RHENIUM (Re)

A by-product of copper and molybdenum production, rhenium is one of the rarest and most expensive metals. A shortage roughly a decade ago forced engineers at General Electric to develop new alloys that could replace rhenium in jet-engine turbine blades.

LEAD (Pb)

Lead consumption is on the rise, chiefly in response to demand for backup batteries and protective sheathing for underground wires. No alternative materials exist for such uses, but new technologies such as long-sought fuel cells could replace lead-based batteries.

Substitute Performance

Excellent

Poor

Element not evaluated

SOURCE: "ON THE MATERIALS BASIS OF MODERN SOCIETY," BY T. E. GRAEDEL ET AL., IN PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES USA, VOL. 112, NO. 20, MAY 19, 2015