a high level of predetermination and have a shorter time course. Any group of cells may respond simultaneously to several specific inductors, the organ that emerges depending upon which sort of inductor first has sufficient cumulative effects. When artificially imposed conditions bring about a "tie," then two organs may emerge side by side, or even from the same cell mass (*4, 17*). Induction is clearly not a trigger event, and progress toward formation of one organ does not interfere with progress toward formation of a different organ from the same cells.

Specific inductors seem to be doing the same thing through the whole course of induction, but in the responding tissue there is finally a sequence of qualitatively different events in response to the cumulative effects of the constant inductive stimulus. Late in the sequence, the responding cells become more firmly committed to a particular course of differentiation. The initiation of cell-specific protein production must be one of the terminal events.

But a specific inductor always elicits many cell types with their diverse arrays of specific proteins. I know of no case at all in which induction elicits just one cell type. The lens is probably the simplest induced structure, and it consists of two, or perhaps three, cell types. Usually a whole organ is induced by a specific inductor, and the distribution of cell types in the organ is not immediately fixed by induction. Recently induced organ primordia have the characteristics of an embryonic field. At first more cells are involved than actually later form the organ, and any part of the early field can be made to form the whole organ. The axes of the organ become fixed in a specific order, and gradually the parts become delimited and eventually established fairly permanently.

The segregation of the parts of a developing organ occurs over a rather extensive period following the first appearance of the organ rudiment as a whole (*8*). The segregation of the parts of an embryonic field is not at all well understood. Probably it involves continued induction from surrounding tissues and even induction among emerging parts of the organ itself. The epithelio-mesenchymal interactions in developing mesodermal and endodermal organs that are being extensively investigated as induction systems (*18*) are examples of segregating embryonic fields.

The highly organized and regulated processes of development begin in oögenesis and end with the death of the animal. Embryonic induction is an integral part of these processes during the transition from a unicellular to a multicellular organism. Studies of induction systems in their organized states continue to provide new information about the role of induction in cell differentiation.

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Cubic Carbides

Solid-state physics explores materials having ionic structure, metallic conductivity, and covalent hardness.

Wendell S. Williams

Transition metals are like modern music—relatively hard to understand. We would expect compounds of the transition metals to be even more puzzling to those seeking harmony between theory and experiment. However, one family of transition-metal compounds, the monocarbides, has the simple and familiar rock-salt crystal structure. The cubic symmetry of this structure simplifies the problems of obtaining good samples, determining their properties, and treating these properties theoretically.

Interest in the transition metal carbides has increased greatly in the last few years because industry and government need better high-temperature materials. The carbides have the highest melting points of any known compounds. In addition, they are chemically inert and extremely hard. In this article I will describe recent progress in interpreting these properties from the point of view of solid-state physics, emphasizing the nature of the binding as suggested by electrical, mechanical, and thermal properties and as inferred from theoretical considerations. Other reviews of the transition-metal carbides have been given by Schwartzkopf and Kieffer (*1*), Samsonov (*2*), Storms (*3*), Westbrook and Stover (*4*), and Costa and Conte (*5*).

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Description of the Carbides

Atoms of the transition metals have inner electronic shells ("*d*-shells") which are unfilled. These elements form three series representing transitions along the periodic table from one closed-shell configuration to the next (Table 1). The transition metals display peculiarities in many physical properties: for example, compared with a metal such as copper, they have large specific heat, high magnetic susceptibility, and high electrical resistivity. These peculiarities have been explained (*6*) by electron-energy-band theory as resulting from a high density of *d*-like electronic states in the solid and a correspondingly high probability of scattering. This characteristic of the transition metals plays an important part in determining the properties of the carbides formed from them.

The transition-metal carbides are "compounds" which can be formed from the transition metals by the addition of carbon. In the case of the group IV and group V monocarbides, here symbolized by MeC_x (where x is somewhat less than one), the hexagonal-close-packed or body-centered-cubic structure of the metal changes to face-centered-cubic in the carbide. The carbon atoms, which have a radius approximately half that of the metal atoms, find stable positions in the spaces between the metal atoms. These positions are called "octahedral interstitial sites," and sometimes the carbides are called "interstitial" compounds.

However, this name incorrectly suggests a low concentration of carbon, since interstitials in metals are infrequent; yet the concentration of carbon in the carbides can approximately equal that of the metal atoms ($x \cong 1$). Although the carbon atoms are widely spaced relative to their radius, they are arranged in a face-centered-cubic lattice having the same lattice constant as the metal lattice. The resulting structure is the NaCl or rock-salt structure: two interpenetrating face-centered lattices (Fig. 1).

A characteristic of the carbides that is particularly interesting to solid-state physicists is the high concentration of carbon vacancies, up to 50 percent in titanium carbide ($TiC_{0.5}$), that can be accommodated in the carbide structure. In metals, vacancies may be produced by irradiation, by quenching from near the melting point, or by plastic straining; however, the concentrations never exceed approximately one hundredth of 1 percent. In the carbides, the vacancies are introduced chemically by adjusting the ratio of carbon to metal in the starting material. Atomic vacancies in solids influence many physical properties: vacancies can scatter electrons and phonons and thus increase the electrical and thermal resistivity; they can accelerate diffusion; and they can hinder the motion of dislocations and thus increase the hardness. Measurements and analyses of some of these effects in the carbides have been carried out and are discussed further on. The vacancies are usually assumed to be randomly distributed, but the possibility of association of defects needs to be studied.

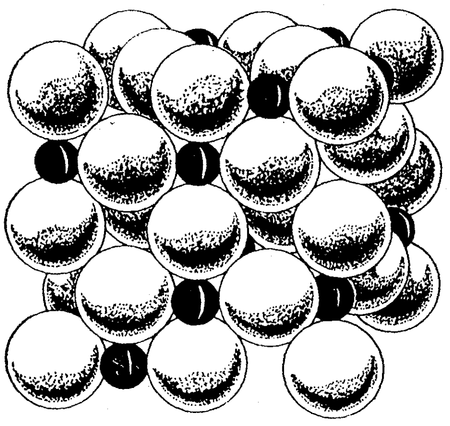


Fig. 1. Rock-salt crystal structure of the transition metal monocarbides. Small spheres represent carbon atoms and large spheres metal atoms. Note high concentration of carbon vacancies. Planes of like atoms, {111}, are glide planes for dislocation motion.

To a chemist, the presence of many carbon vacancies in a compound indicates that in the solid phase the compound has a wide range of solubility. Hansen (*7*) has summarized earlier phase-diagram work, and Sara (*8, 9*) has recently redetermined four of the diagrams (Fig. 2). It is interesting that the group IV transition metals form only monocarbides (MeC_x), whereas the group V transition metals also form

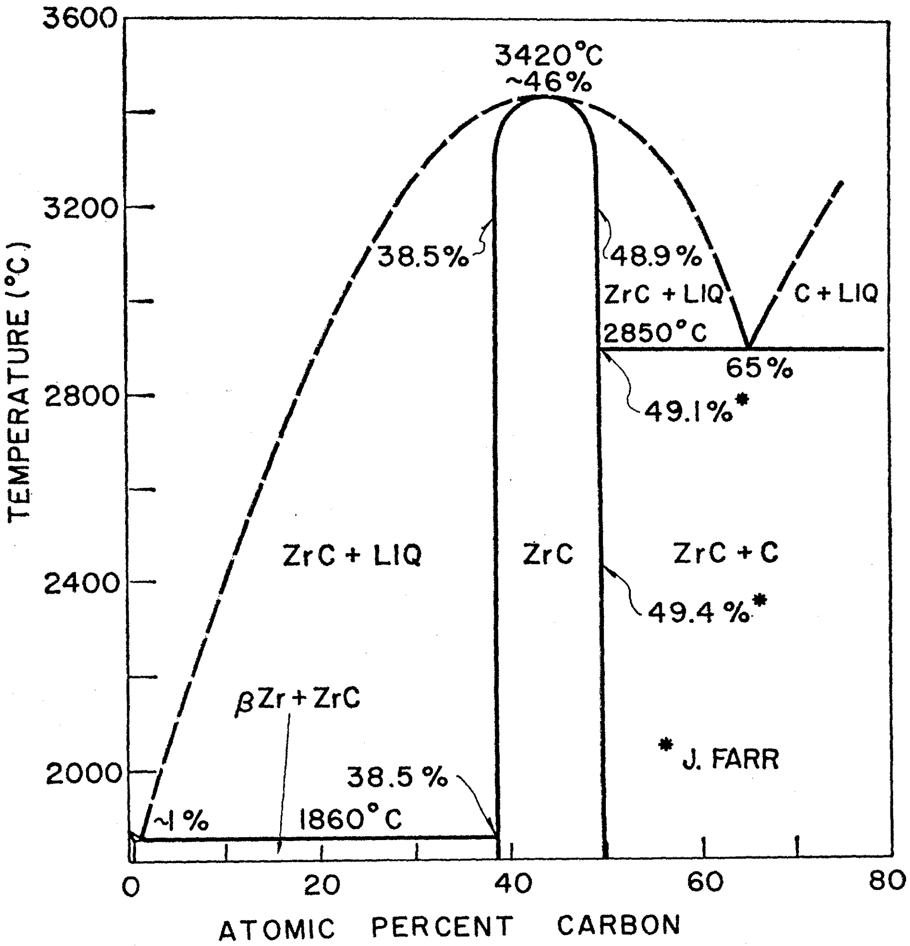


Fig. 2. Phase diagram for Zr-C system. Note high melting point of zirconium carbide, dependence of melting point on the ratio of carbon to metal, and the width of the ZrC phase. These features are characteristic of the carbides. [Reprinted from *8*]

a carbide of the form Me_2C. The situation in the carbides of the group VI metals is more complex.

Carbide single crystals, such as those used in many of the experiments described here, cleave along {100} planes in the rock-salt structure in the same manner as NaCl. The cleavage surfaces are mirrorlike. The extreme hardness and brittleness of the material are evident when samples are prepared for investigation; one of the major problems to be discussed is the physical basis for these characteristics.

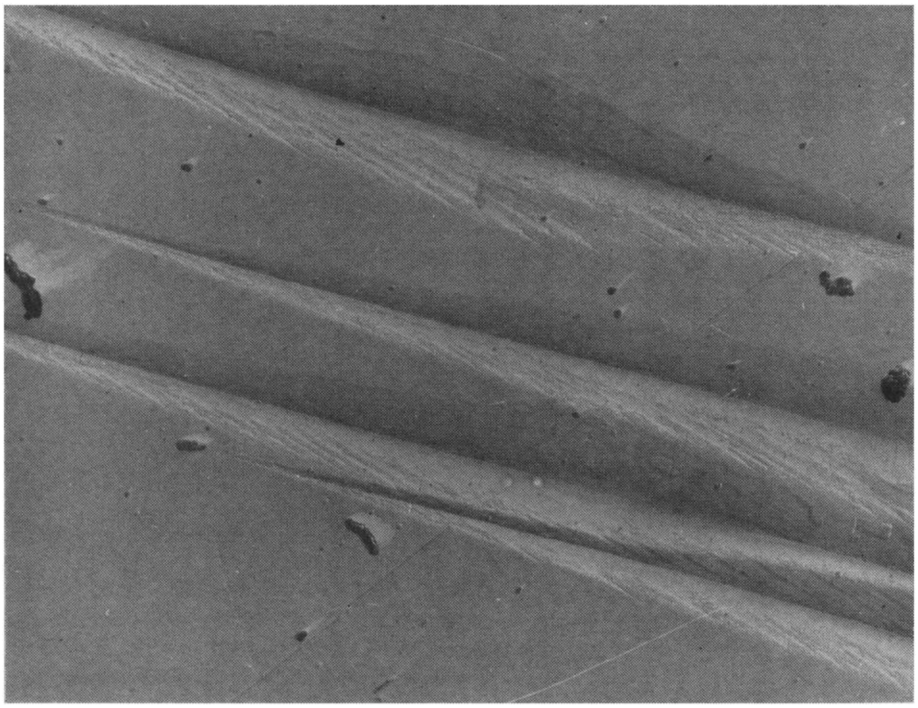


Fig. 3. Microhardness indentations in {100} cleavage surface of a single crystal of titanium carbide. Participation of dislocations is indicated by slip lines. Electron micrograph of surface replica by R. Sprague (*13*) (× 5000).

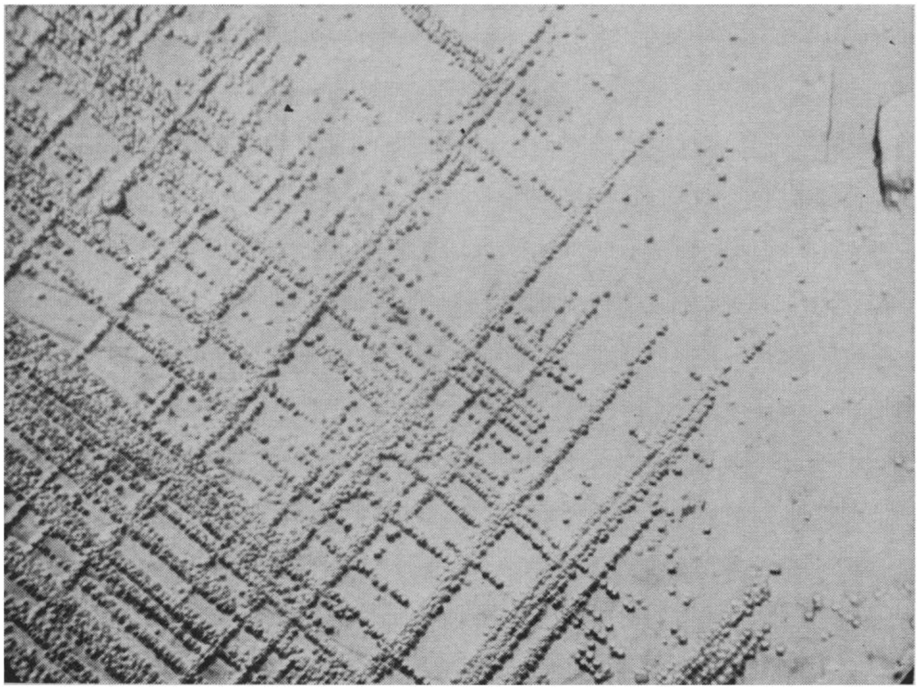


Fig. 4. Etch pits at points of emergence of dislocations through {100} cleavage surface of plastically strained TiC single crystal. Etchant: boiling H_2SO_4. Diagonal rows of pits show that dislocations glide on {111} planes (× 500). [Reprinted from *18*]

Hardness

The most useful property of the carbides to date is their extreme hardness. Cutting tools of cemented WC and TiC are commonly used industrially, and dentists are now using drill tips of these materials. Although the stress required to make a sample flow plastically is the quantity of greatest theoretical interest, the carbides fracture before yielding plastically over large volumes at room temperature. Hence, measurements of microhardness, which is proportional to yield stress, are made instead. Carbide samples can be indented by diamond over a very small region without being fractured; the size of the impression and the applied load can then be measured.

With this technique, several workers (*10, 12, 13*) have found that the hardness of TiC increases with the ratio of carbon to metal. Evidently the addition of carbon atoms increases the strength of the binding in titanium carbide. In tantalum carbide, the situation is more complex: the curve for hardness plotted against x has a maximum (*14, 15*).

It is well established that plastic flow in a crystalline solid results from the formation and motion of dislocations and that dislocation mobility increases with increasing temperature. The participation of dislocations in microhardness indentations at room temperature (despite their low mobility) has been demonstrated for WC by Corteville and Pons (*16*) and for TiC by Williams (*13*) (Fig. 3). Softening of TiC in high temperature hardness testing has been studied by Westbrook (*10*) and Fitzgerald (*11*).

Westbrook and Jorgensen (*17*) have discovered recently that the presence of water on the surface of a TiC sample permits "indentation creep," a gradual softening of the surface under the indenter. The influence of polar molecules on the formation or motion, or both, of dislocations is another clue to the nature of the binding in the carbides, but the details are not yet clear.

High-Temperature Plastic Flow

The brittleness of crystals of TiC at room temperature gives way to a capacity for substantial plastic strain at high temperatures. Williams and

Schaal (*18*) performed bend tests on such crystals at temperatures above 800°C (this temperature is not a sharp "brittle-ductile" transition temperature). We found that the presence of dislocations in the carbides can be revealed when the carbides are etched with boiling sulfuric acid. Using this technique, we established that the slip plane in TiC is {111} (Fig. 4). This result has since been confirmed by Hollox (*19*) and by Brookes (*20*).

That dislocations should glide on this particular crystallographic plane is surprising, since in ionic solids with the same crystal structure as the carbides, a different plane, {110}, is active. A possible explanation is that dislocation glide will occur on the planes that are the most widely separated, and hence least tightly bound, unless there is some other prohibition. In ionic solids, there is such a prohibition in the form of electrostatic forces. In face-centered-cubic metals and diamond-cubic semiconductors, however, glide is on the close-packed {111} planes. In the carbides, the occurrence of {111} glide suggests that the bonding is not primarily ionic but, instead, covalent or metallic. A band structure calculation (*13*) shows that, although there is some ionicity, the presence of a few conduction electrons partially screens these forces and that the binding is primarily covalent, with negligible metallic contribution of the kind found in face-centered-cubic metals. Hence the simple observation of the crystallographic plane on which dislocations glide tells something meaningful about the nature of the binding.

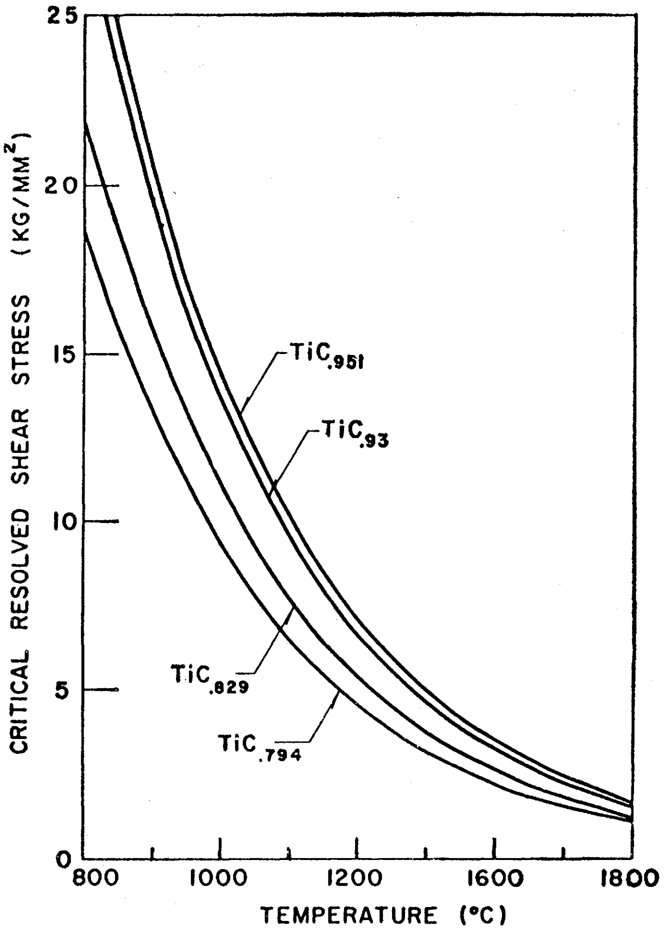


Fig. 5 (above). Dependence of stress for plastic yielding on temperature for single crystals of titanium carbide with various values of carbon-to-metal ratio, x. Yield stress increases with increasing x. [Reprinted from *21*]

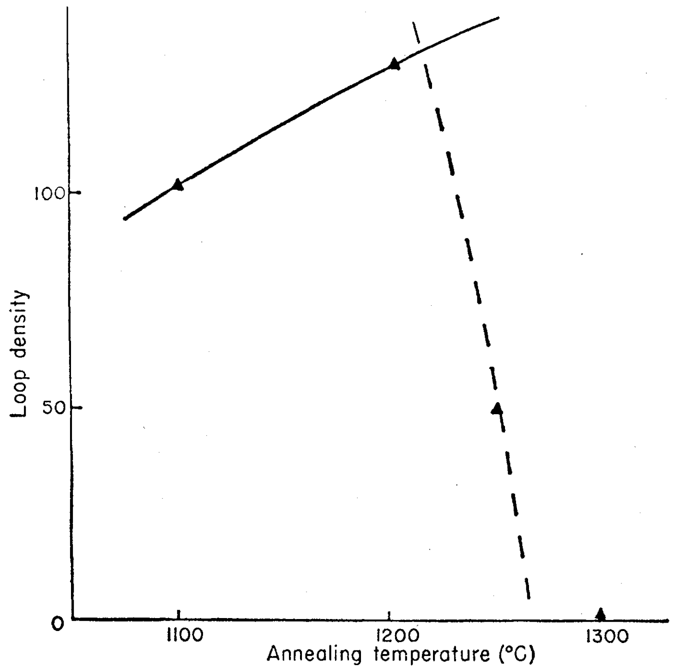


Fig. 6 (top right). Annealing behavior of dislocation loops left by moving dislocations in TiC deformed at high temperature. Vacancy diffusion down dislocation pipes is thought to be the annealing mechanism. [Reprinted from *23*]

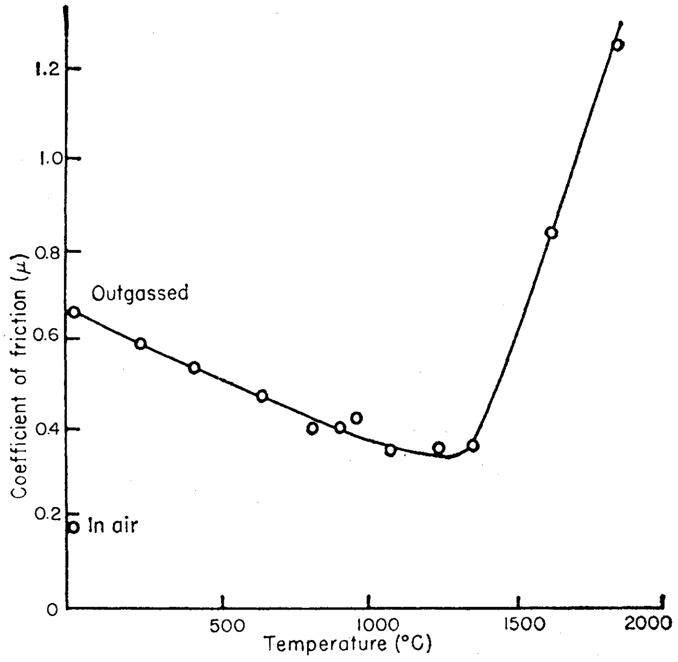


Fig. 7 (bottom right). Coefficient of friction of TiC at elevated temperatures. Rapid rise around 1000°C is thought to result from onset of diffusion. [Reprinted from *20*]

Table 1. Section of the periodic table showing six transition metals, of groups IV and V, and their electronic structures. These metals form the monocarbides discussed in the text.

IV	V
Titanium (Argon core + $3d^2 4s^2$)	Vanadium (Argon core + $3d^3 4s^2$)
Zirconium (Krypton core + $4d^2 5s^2$)	Niobium (Krypton core + $4d^4 5s^1$)
Hafnium (Xenon core + $5d^2 6s^2$)	Tantalum (Xenon core + $5d^3 6s^2$)

The mobility of dislocations in TiC is thermally activated (*18, 22*), with activation energy 1.5 ev below 1200°C and 3 ev between 1200° and 1700°C. According to electron transmission microscopy of thin foils of TiC reported by Hollox and Smallman (*23*), this "transition" temperature is approximately that at which the annealing of dislocation loops, left as debris by glide dislocations, begins to be important through the mechanism of diffusion of vacancies along dislocations (Fig. 6). Above this temperature, in the range 1200° to 1700°C, the activation energy for creep in the early stages before strain hardening begins is 3 ev (*13*), the same as that for yield stress. This correlation is expected from theoretical considerations, as shown by Haasen (*24*).

The yield stress at high temperature increases with increasing carbon-to-metal ratio (*21, 22*). As with microhardness at room temperature, adding carbon increases the strength of the binding in the solid. As new mechanisms affecting dislocation mobility become important at high temperatures, more detailed considerations are needed to explain the precise influence of carbon on the binding strength; but the existence of influence has been established. At low temperatures, the primary limitation for dislocation mobility is apparently the intrinsic lattice resistance, called the Peierls force (*18, 21*). Evidently, in TiC, dislocations are not seriously impeded by vacancies.

Elastic Moduli and Bending

The acoustic velocity of an elastic wave is proportional to the square root of the elastic modulus (stiffness) of the material. Modern techniques for determining the various elastic stiffness constants of single crystals employ ultrasonic waves. Measurements of this kind have been made on single crystals TiC by Gilman and Roberts (*25*) and by Bernstein (*26*). The values obtained show that the elastic forces in TiC are strong.

From the measured elastic constants, Bernstein (*26*) calculated a Debye temperature of 734°K for TiC. From x-ray studies, Houska (*27*) obtained a similar value, along with the additional information that the metal and carbon atoms in the carbide have approximately the same effective Debye temperature for their separate vibrations, which is another indication of the nature of the bonding in this compound.

Although the carbides are brittle at room temperature, they can, like any brittle material, be deformed elastically without fracture if the surfaces are free from flaws. Williams and Schaal (*18*) discovered an electrolytic polishing technique that removed cleavage steps and nicks from the surfaces of single crystals of TiC. Samples so treated were bent to elastic strains of ≈ 2 percent, and one sample supported 800,000 pounds per square inch (56 × 10^9 dynes per square centimeter). Unpolished crystals showed on the average only one-fourth the strength of polished crystals. Subsequent etching showed that no new dislocations were produced in bending, even at stress values approaching the theoretical shear stress. This situation is described by the statement that dislocation mobility is very low in TiC at room temperature (*18, 21*).

Friction and Thermal Conductivity

Mordike (*28*) and Brookes (*20*) have studied the temperature dependence of the coefficient of friction of TiC with respect to TiC (Fig. 7). The coefficient of friction decreases slightly as temperature increases from room temperature to approximately 1000°C and then rises rapidly with increasing temperature. The initial decrease may be due to the smoothing of asperities by plastic flow, which becomes easier as the temperature increases. Mordike (*28*) and Brookes (*20*) interpret the rapid rise near 1000°C as being due to increased adhesion resulting from diffusion. The temperature is approximately one-half that of the melting point, at which diffusion usually begins to be important in metals. Other evidence for diffusion effects in TiC was obtained by Hollox and Smallman (*23*).

The thermal-conductivity behavior of the carbides illustrates their mixed binding: heat is transported by electrons, as in metals and in semiconductors, and by phonons (quantized lattice vibrations), as in non-metals.

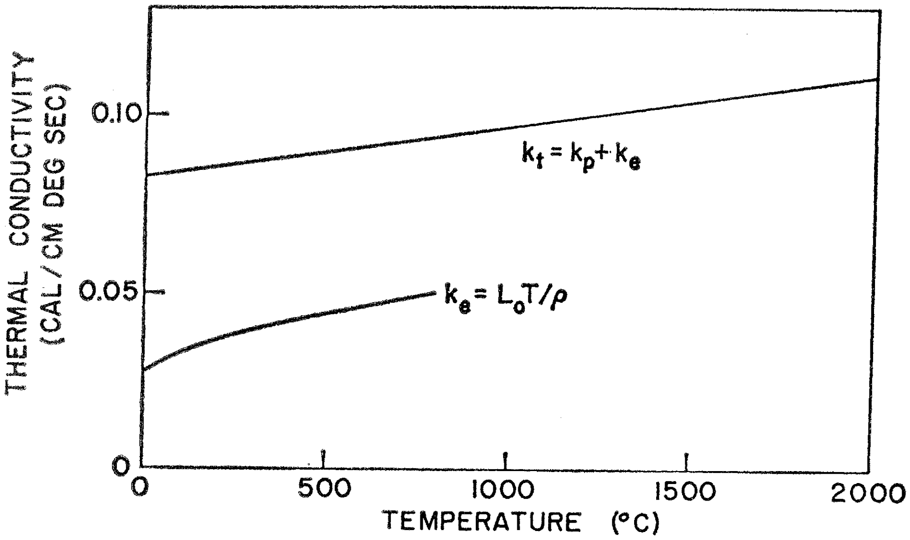


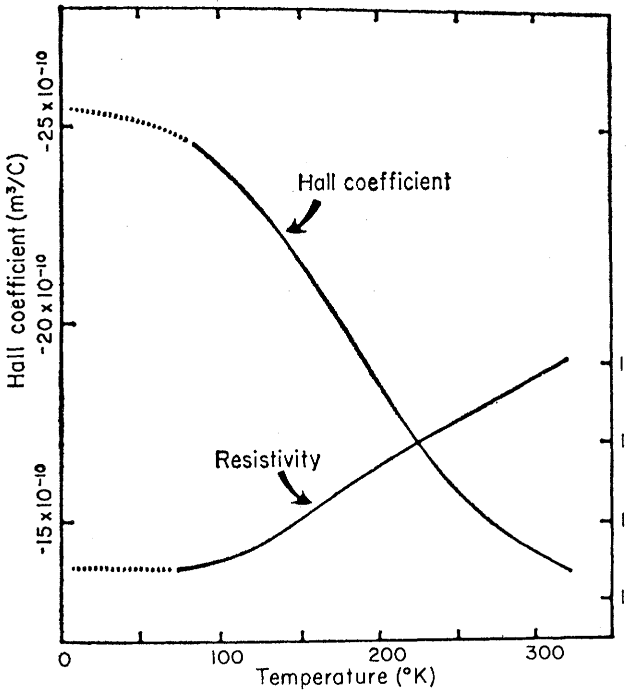
Fig. 8. Thermal conductivity of TiC at elevated temperatures. Total conductivity is the sum of the electron and phonon contributions. Electron contribution, k_e, has been calculated from measured electrical resistivity (*27*). Rise in total conductivity with increasing temperature is a consequence of the complex nature and defect structure of the material (*13*).

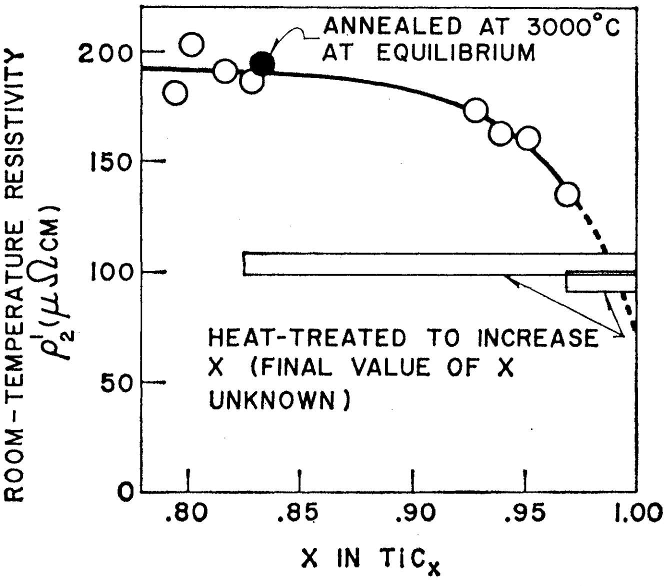
However, these two contributions, k_e and k_p, to the total thermal conductivity, k_t, do not vary with temperature as anticipated from these analogies. Extensive measurements on the carbides by Taylor (*29*) show that k_t increases with increasing temperature (Fig. 8). By application of a relation between electrical and thermal conduction by electrons (the Wiedemann-Franz law, $k_e = LT/\rho$, where L is a constant, T is temperature, and ρ is electrical resistivity), Taylor determined that k_e increases with increasing temperature instead of being constant as with normal metals, and that, by subtraction, k_p is approximately constant instead of decreasing as $1/T$, which is the usual behavior. This apparently strange behavior has been attributed to the defect structure and complex binding of the carbides (*13*).

Electrical Resistivity

The electrical resistivity, ρ, of carbides has been another puzzling characteristic. The room temperature value for stoichiometric TiC ($\sim 60 \times 10^{-6}$ ohm-cm) is high for a metal and decreases only 10 percent at liquid-helium temperature instead of becoming less than a thousandth of the value at room temperature, as with most metals (Fig. 9). Hollander (*30*), using single crystals of TiC, reported some measurements illustrating these points; and Piper (*31*) and Williams (*32*) measured the Hall coefficient (a quantity which permits calculation of the effective number of conduction electrons). The number of conduction electrons was found to be small, only 0.04 per atom, compared with about 1 per atom for copper. Furthermore, Piper discovered that the number of conduction electrons decreases by a factor of two on cooling to liquid nitrogen temperatures.

A review (*32*) of the large spread in values in earlier determinations of ρ for TiC (from 35 to 250 $\times 10^{-6}$ ohm-cm) led to the hypothesis that the major reason for this variation is the wide variability in carbon-vacancy content in these materials. A study (*32*) of the influence of vacancy concentration on ρ in TiC crystals supported this hypothesis and showed that near the stoichiometric composition, carbon vacancies have ten times the scattering power of vacancies in copper (Fig. 10). This unusual result was attributed to the small number of conduction electrons and an effective charge on the vacancy. A different interpretation has been proposed recently by Lye (*13*) on





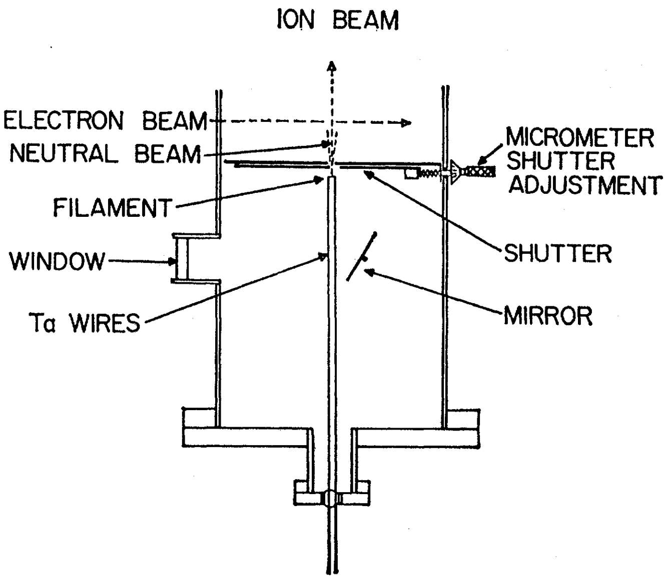


Fig. 9 (above). Dependence of electrical resistivity of TiC on temperature. Note relatively small slope and relatively high residual resistivity compared with normal metals. A high concentration of defects (carbon vacancies) is thought to be responsible (*32*). [Reprinted from *31*]

Fig. 10 (top right). Influence of carbon vacancies on electrical resistivity of TiC. Vacancy concentration $= 1 - x$. Scattering power near $x = 1$ is ten times as great as for vacancies in copper. [Reprinted from *32*]

Fig. 11 (bottom right). Experiment for measuring the rate of vaporization of a tantalum carbide surface at high temperatures and for determining the molecular species in the vapor (*37*).

the basis of an energy-band calculation for TiC. Lye believes that the high scattering power of carbon vacancies is due to a rapid variation in density of electron states near the Fermi level. He also studied the thermoelectric power of TiC and developed an interpretation which depends on this same density-of-states variation (*33*).

A hypothetical carbide with no vacancies should still have a large resistivity at room temperature (*32*). This resistivity is simply a consequence of the small number of conduction electrons, since their mobility is relatively high (~25 cm^2/volt-sec). The small concentration of conduction electrons is predicted by Lye's band structure. This situation is the reverse of that in titanium metal, where the mobility is low due to the high density of *d*-states at the Fermi level, but the concentration of conduction electrons is much higher than for TiC; the product, which is proportional to the conductivity, is about the same for Ti and for TiC.

An alternative interpretation of the resistivity behavior has also been discussed (*32*). A high and temperature-insensitive resistivity can be produced by magnetic disorder scattering. Although there is no evidence of magnetic disorder in TiC, Costa and Lallement (see *34*) have found that a similar material, PuC, is antiferromagnetic.

Melting Point

The transition-metal carbides have melting points in the range 3000° to 3900°C (*1*). The melting points are all far higher than those of the corresponding transition metals, and, in the case of TiC, the values differ by a factor of two. The role of carbon in increasing the melting points so dramatically needs to be understood.

The Lindermann melting rule is helpful here:

$$T_m = \left(\frac{\theta^2}{C}\right)\overline{A\,V}^{\frac{2}{3}}$$

where T_m is melting point in degrees Kelvin, θ is the Debye temperature, C is a constant, $\overline{A}$ is the average atomic weight, and $\overline{V}$ is the average atomic volume. [The use of the rule with NaCl-type compounds has been discussed by Kaufman (*35*).] According to this rule, the melting point increases as the square of the Debye characteristic temperature, that temperature at which all the modes of vibration of the lattice are excited. The Debye temperature is determined primarily by the "stiffness" of the interatomic forces and increases with increasing stiffness. The Debye temperatures of the carbides are unusually high (734°C for TiC at 298°K, compared with 396°C for Ti). Hence, the increase in melting point can be understood as resulting from the increase in the strength of the binding in the solid introduced by the carbon atoms.

Vaporization

The way in which a hot solid vaporizes gives evidence concerning the nature of the binding in the solid. Vapor species can be determined by mass spectrometric analysis. Chupka *et al.* (*36*) studied the solid-vapor equilibrium in the Ti-C system and found no compound vapor species in abundance, only atomic Ti and C. Schissel and Williams (*37*) investigated the free-surface vaporization of TaC and found only Ta and C atoms in the

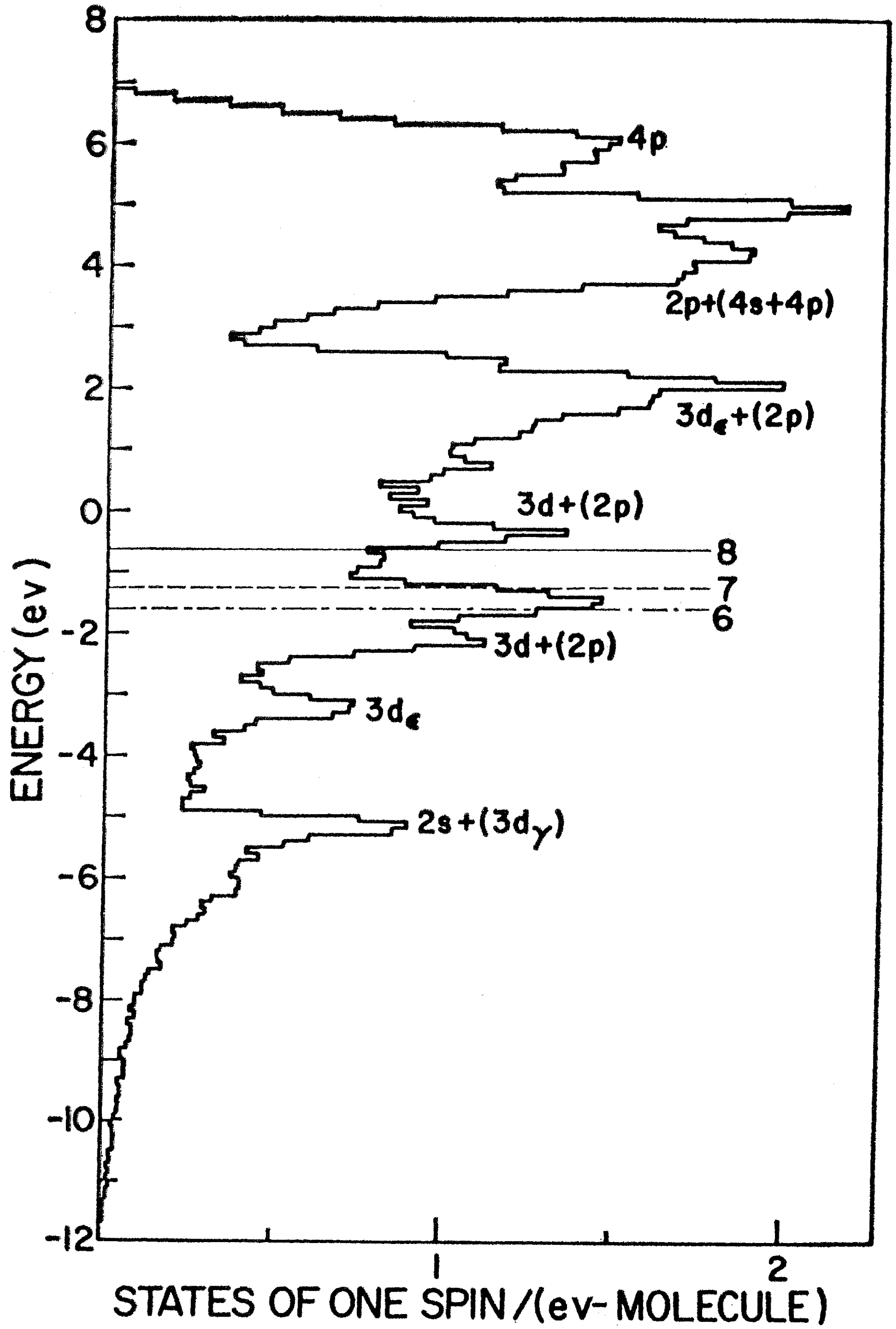


Fig. 12. Density-of-states curve for electrons in TiC, calculated using tight-binding approximation and based on optical reflectivity data. From this investigation, the binding in TiC is deduced to be complex covalent and ionic (*13, 48*).

vapor (Fig. 11). Although not all the relevant systems have been studied, it appears that the transition-metal carbides vaporize by dissociating to the monatomic elemental species: MeC (solid)→Me(gas) + C(gas).

What is implied by this information? The binding apparently is not exclusively ionic, since diatomic molecules of the form MeC do not appear in the vapor as they do with ionic solids of the same crystal structure as the carbides. Neither is the binding exclusively covalent, since complex molecules of the form Me_2C or MeC_2 do not appear as they do in the vaporization of SiC (*38*), a covalently bonded material which, like the transition-metal carbides, is 50 percent carbon. Instead, it appears that many atoms participate in the binding. The complex binding forces are lost as vaporization takes place, and complete dissociation results. It will be seen later that this model is consistent with the ionic and covalent bonding in the carbides implied by the electron energy band structure calculated by Lye (see *13*).

As a compound undergoes free-surface vaporization, changes in the composition of the remaining solid may occur. For TaC, carbon leaves the surface faster at high temperatures than does Ta; for TiC, the reverse is true. This behavior is controlled by the free energy of formation of the compound and the sublimation energies of the elements (*39*), and it is possible for x to be unchanged on vaporization ("constant-boiling" or "congruent vaporization"), as found for $NbC_{0.75}$ by Fries (*40*). Time-dependent changes in composition of materials do not please design engineers, but this characteristic can be exploited for research purposes. Crystals of TiC have been baked to reduce the carbon vacancy concentration in a study of electron scattering (*32*).

Electron-Energy-Band Structure

Solid-state physics has developed techniques for calculating the approximate distribution of electrons in a solid with respect to energy and also for suggesting their spatial distribution. This information can then be used to develop a model for the type of binding in the solid: metallic, ionic, covalent, or some combination of these. (These terms are not very satisfactory in the light of current knowledge, but they have historical significance and are retained for convenience.) Once the type of binding is determined theoretically, inferences can be made about physical properties and compared with experiment. Such a program was initiated by Lye (*13*) for titanium carbide, with the use of a computer program written by J. W. McClure and based on an approximation used by Slater and Koster. Since it is very difficult to make such calculations entirely from first principles, it was decided to ground the calculations in experimental information. Optical reflectivity in the ultraviolet region was chosen as the most useful type of information for this purpose. The measurements were made at Cornell University by E. Logothetis under P. Hartman's direction. Lye used the optical data to guide the choice of parameters required for the semiempirical calculation of band structure.

The resulting energy-band structure (*13*) showed some features similar to other efforts, by Bilz (*41*), Costa and Conte (*5*), and Ern and Switendick (*42*), a high and rapidly varying density of states of *d*-like character, related to the *d*-states in the transition metals themselves mentioned earlier (Fig. 12). However, other features of Lye's calculation have several important, different implications: there is some net transfer of charge from carbon atoms to titanium atoms, so part of the binding is ionic; covalent bonding occurs not only between carbon and titanium atoms, but also between titanium atoms and between carbon atoms. Also, the type of covalent bonding that exists between metal atoms is similar in origin to the "band bonding" of the transition metals, an effect which appears to account for their relatively high melting points: the high density of unfilled *d*-states in the free atoms constitutes a relatively low energy reservoir for valence electrons of higher energy when the solid is formed, thus lowering the total energy of the system.

Since much has been written about the nature of the bonding in the carbides, it is important here to make clear what is new. The notion that charge is transferred from non-metal to metal in the compound has been advanced by Umanskii (*43*), Kiessling (*44*), Robins (*45*), Dempsey (*46*), Costa and Conte (*5*), and Juretschke and Steinitz (*47*). These workers' arguments were based on experimental evidence and some theoretical considerations; the band-structure calculation by Lye adds theoretical support to the position. The presence of covalent bonding was also appreciated by some of these workers, but, again, this notion has now been made more precise. Although charge transfer was widely accepted, its complex influence on the binding was not emphasized prior to Lye's work. The presence of relatively few conduction electrons to screen the ionic interaction makes the ionic contribution substantial.

The covalent bonds found by Lye for the carbides have a directed nature that would be expected to lead to a large stiffness with respect to elastic deformation. Such is indeed the observed behavior. The breaking of these bonds, which is required for dislocation motion, should take considerable energy and lead to a high Peierls force. This feature is also observed. Both elastic and plastic deformation are also resisted by the ionic bonding.

Summary and Conclusions

Because of a national need for new high-temperature materials, modern experimental and theoretical techniques of solid-state physics have been applied to the study of the transition-metal carbides, a class of hard, brittle, semimetallic solids with exceptionally high melting points. Also, existing knowledge of the physics underlying the behavior of the principal classes of inorganic solids (ionic, metallic, and covalent) has been applied to the carbides. Although many details remain to be investigated, the principal features of the electrical, thermal, and mechanical behavior of the carbides have been established. These features include high elastic constants; high electrical and thermal resistivity (compared with noble metals), which is unusually sensitive to point defects; small and temperature-dependent concentration of conduction electrons; low dislocation mobility; vaporization to the elements; and sensitivity of various properties to the carbon-to-metal ratio.

These observed features can be deduced from a general understanding of solids combined with a recently calculated energy band structure of a typical carbide. Hence, one of the goals of solid-state physics—achieving a fundamental understanding of the properties of a class of solids—is being reached, and harmony is emerging from dissonance.

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48. I thank R. G. Lye for permission to use this figure in advance of publication.

A Revised Charter for the Science Foundation

A bill has been proposed which could make NSF more effective in meeting contemporary demands.

Emilio Q. Daddario

On 18 January 1966, the Committee on Science and Astronautics of the House of Representatives unanimously approved a report (*1*) of its Subcommittee on Science, Research and Development in which they recommended certain changes in the structure and functions of the National Science Foundation.

The Subcommittee's report was the culmination of a study that began late in 1964 and ran throughout 1965. It was the first comprehensive legislative review of the Foundation in the 15 years of NSF's existence, and it was preceded by a careful factual survey of the Foundation's operations which had been made at the Subcommittee's request by the Library of Congress (*2*).

Seven weeks of hearings then went into this effort, plus additional weeks of executive consideration by the Subcommittee itself.

As a result of this work and of the full Committee's backing, I have introduced in the House H.R. 13696, a bill to effect the changes recommended. We expect to send this bill to the House floor for debate by spring.

What does the bill provide and what do we intend it to do?

Before launching into a description, I should like to make a few brief comments regarding the rationale and the philosophy behind this legislation.

The subcommittee's report, which is the basis for H.R. 13696, is a critical one and was so intended. It is not critical of the Foundation as an institution, however, nor of its personnel. Our criticism is directed toward the Foundation's relatively slow evolution in relation to the swelling, fast-changing contemporary problems of the nation and in regard to the Foundation's underutilized potential as a member of the Executive's scientific and technological family.

In stating this criticism we do not seek to assess fault. The modern world being what it is, I doubt if we could point any fingers with accuracy even if we spent the time necessary to attempt it. Moreover, there is little doubt in my mind that Congress—which until recently has never bothered to exert real oversight of the Foundation—is partially responsible for the situation which our report describes.

Let me summarize that situation by quoting from the report:

> The Foundation is operating, and is largely organized to operate, in a manner which was satisfactory a decade ago but which does not appear adequate for either today or tomorrow. . . . The fact is that the Foundation has not kept pace with the demands of society nor adequately oriented itself within the shifting machinery of government. . . . Fundamentally, it may be said that the Foundation has functioned, and still does, in a manner that is

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The author, who represents the Hartford district of Connecticut, is chairman of the Subcommittee on Science, Research and Development of the U.S. House of Representatives Committee on Science and Astronautics, Washington, D.C.