9 September 1960, Volume 132, Number 3428 SCIENCE

CURRENT PROBLEMS IN RESEARCH

Ultrasonic Absorption in Solids

How high-frequency sound is damped by imperfections in solids.

Thomas S. Hutchison

The main interest of the ancients in the absorption of sound was an indirect one. It concerned the fabrication of bells, which, until about the 8th century, were made of beaten iron sheets riveted together. About then, the practice of casting of bells, or "bell founding," began. For the latter, the preferred composition of "bell metal" became, by the 16th century, copper and tin in the ratio of about three to one. Both the practice of working the iron sheets by beating and that of alloying, in the case of "bell metal," reduce the movement of imperfections in the metal, and this, as will become clear from the discussion, gives rise to a decrease in the attenuation of acoustic waves, so giving clear and prolonged ringing.

It is, however, only during the present century that most of the real mechanisms of acoustic damping have become known. The elucidation of the nature of these mechanisms had to await a clearer picture of the actual atomic nature of solids (*1*).

The techniques of modern physics have produced this revelation. Solids are now known to be mostly crystalline; this means that the atoms of which they are built are arranged in space in a regular pattern, the planes of a similar nature being parallel over the whole volume of the crystal. Such single crystals can now be grown in many instances to a volume of several cubic inches.

The use of x-ray diffraction techniques has made it possible to measure the exact positions of the atoms in the crystal lattice. Electron diffraction has given insight into the nature of the surfaces of solids, and, more recently, neutron diffraction, with radiations much more penetrating than either x-rays or electrons and with characteristics of scattering by atoms different from either, has revealed the positions of certain atoms which are invisible to x-rays.

Optical microscopy, complemented by the use of polarized light, is now a standard technique of the metallurgy laboratory for the examination of prepared solid surfaces. The wealth of experience that has been accumulated now enables the technologist to deduce the bulk nature of the solid element or alloy from the evidence of the surface.

Lattice Imperfections

Of more recent interest is the examination of the nature of the lattice imperfections which occur in natural and fabricated solids. The examination of solids by ultrasound is of importance primarily in the elucidation of the nature of the imperfections rather than in elucidation of the nature of the perfect crystalline lattice.

Let us then deal with some of the different kinds of imperfections which are always found in solids, even in solids produced under the most careful growth conditions.

First of all, the solid element is not pure. Foreign atoms occur in two kinds of position in the lattice. They may take the place of one of the solvent atoms in the substitutional kind of alloy or be squeezed in between the atoms of the element in interstitial positions. It is found that the main factor governing the choice of kind of alloy is one of size of the foreign atom relative to size of the matrix atom. If the atoms of solute and solvent are within about 15 percent of each other in size, then the alloy is likely to be substitutional, whereas interstitial atoms are generally much smaller than solvent atoms and can as a consequence be accommodated in the interstices of the geometrical atomic structure. The presence of quite small numbers of foreign atoms markedly affects many of the physical characteristics of the solid. This is not surprising, since it may be easily calculated that in an alloy with, say, one foreign atom per thousand lattice atoms, few points in the alloy, if it is homogeneous, are more distant from a foreign atom than about eight atomic spacings.

At temperatures above absolute zero the equilibrium configuration of the atoms in the lattice is such that point defects, such as atoms out of their normal positions, must exist. The configurational entropy S of the lattice containing such defects contributes to a lowering of the free energy F in the expression $F = U - TS$, where T, the temperature, is not zero. The condition of minimum free energy is in all such systems that of greatest likelihood in equilibrium.

The two kinds of single point defect commonly encountered are the Schottky type and the Frenkel type; in the Schottky type the atom out of position is located at the surface while in the Frenkel type the misplaced atom is in

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an interstitial position. It is common for such point defects to exist in clusters. Such defects may interchange positions with atoms of the lattice or with foreign atoms, interchanges that give rise to self-diffusion or to impurity diffusion. In ionic solids these defects are charged and their movement constitutes an electrical current, the conductance being strongly dependent on temperature, as are all diffusion processes.

In addition to point defects, investigation of the plastic properties of solids has revealed different kinds of line defects or "dislocations." Figure 1 shows the simplest of these dislocations and the manner in which it can move through the solid. A theoretical calculation of the applied shear stress that will cause two planes of atoms in a crystal to slip relative to each other gives a value which is of the order of 1000 times greater than the highest experimentally observed yield stress. Taylor (*2*), Orowan (*3*), and Polanyi (*4*) first suggested that the mechanism of slip takes place through the movement of dislocations across a slip plane and were able by this means to account for the small value of the observed shear strength. This idea has been immensely fruitful in the explanation of a great number of mechanical properties of solids. Recently the work of Hirsch (*5*) and his co-workers at Cambridge has revealed by electron optics the very existence of dislocations.

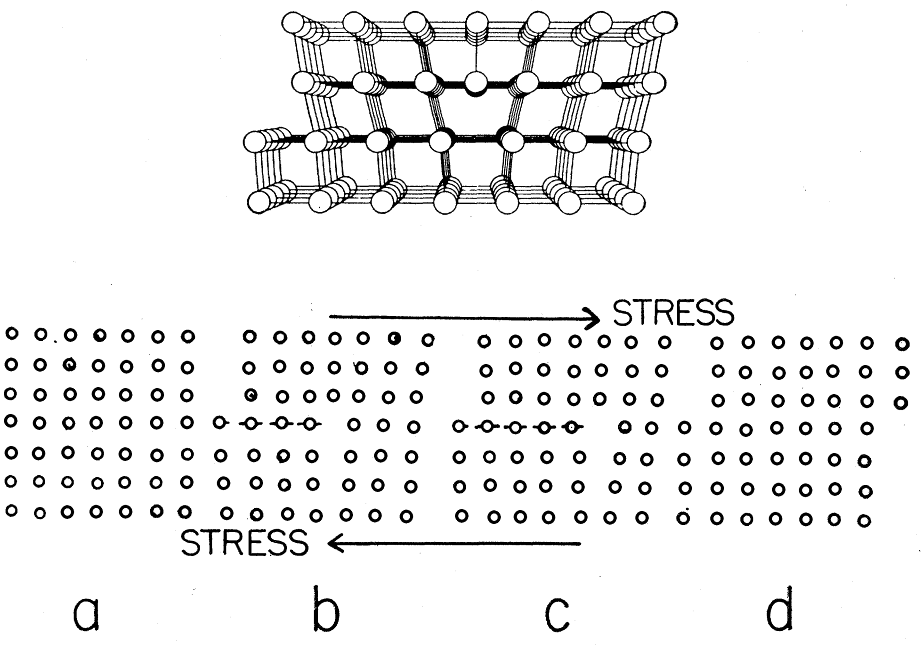

Fig. 1. The upper figure shows a positive edge dislocation. The lower sequence *a*, *b*, *c*, *d* shows how such a dislocation, once generated, may move to the right under a shearing stress; *b* corresponds to the upper figure while *d* shows the resulting slip displacement when the dislocation has moved right across the slip plane.

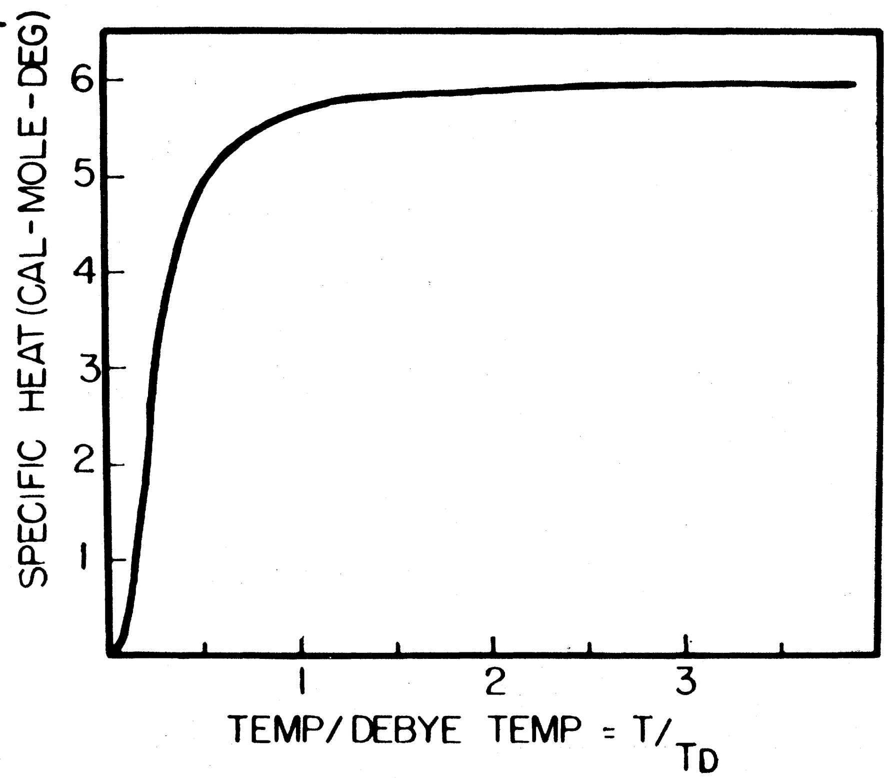

Fig. 2. Specific heat of a solid as a function of temperature. The temperatures are quoted as ratios T/T_D where $kT_D = h\nu_{max}$ (see text).

Dislocations occur as a network throughout the crystal, being anchored at the crossing points. Point defects and impurities may also pin down the dislocation loops at intermediate points. The number of dislocations through each square centimeter of solid crystal is generally of the order of 10^5 to 10^8 and may be increased in metals to about 10^{12} by plastic deformation.

The lattice of atoms in a solid is in continuous vibration due to thermal energy. The particle aspects of the normal modes of vibration are called "phonons" and also constitute imperfections in the crystalline solid. The energy E of a phonon is given by the relation $E = h\nu$, where ν is the frequency of the lattice vibration considered and h is Planck's constant ($= 6.62 \times 10^{-34}$ joule-sec). The vibrations form a spectrum varying from low frequencies up into the infrared region. Figure 2 shows the specific heat for a crystal at different temperatures where the temperatures are quoted as a fraction of the Debye temperature T_D which is defined by $kT_D = h\nu_{max}$, where k is the Boltzmann constant ($=1.38 \times 10^{-23}$ joule/°K) and ν_{max} is the highest frequency of phonon vibration in the lattice. From the graph it can be seen that at temperatures above T_D the specific heat, which is a measure of the amount of energy which must be added to raise the temperature by a specific amount, is almost constant, indicating that all the modes of vibration are excited, while at low temperatures the specific heat drops off because thermal agitation is not strong enough to excite the high energy vibrations of the crystal.

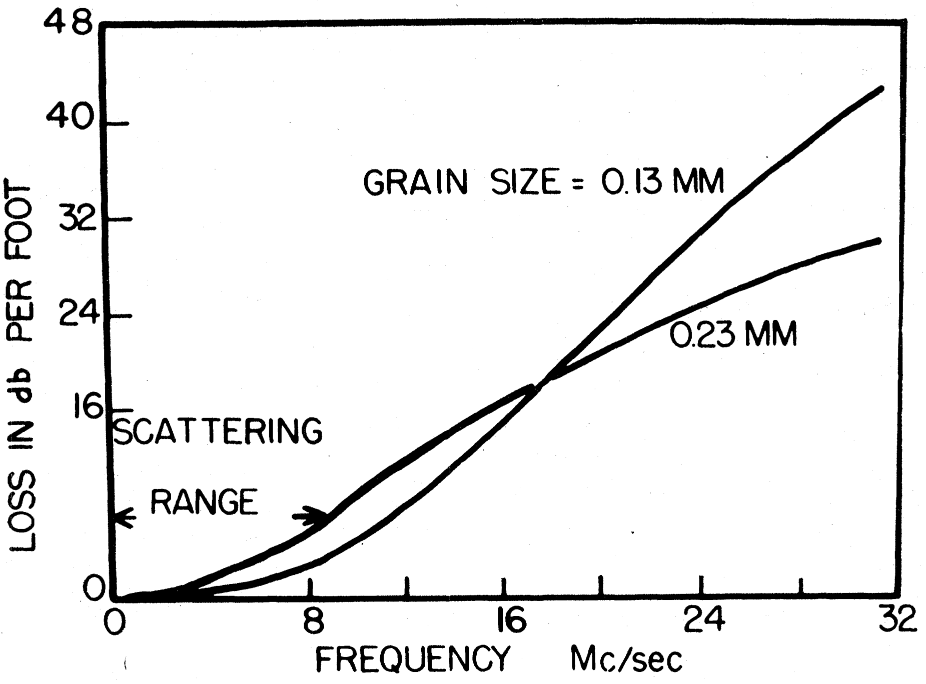

Fig. 3. Attenuation of high-frequency sound by scattering in two aluminum rods of different grain sizes. The larger grained material, being closer in grain size to the acoustic wavelength at the lower frequencies, gives the greater Rayleigh scatter. When the wavelength becomes shorter than the grain size, the attenuation becomes independent of frequency.

The interaction of electrons, phonons, and defects establishes thermal equilibrium in the lattice, while scattering by phonons and defects of the charge carriers—electrons and "holes"—endows the solid crystal with electrical resistivity. The flow of heat in good conductors such as metals is mostly by the passage of electrons, and in poor conductors, by the diffusion of phonons. This phonon diffusion does not proceed at the velocity of sound as it might be expected to do since thermal vibrations are merely extremely high frequency acoustic waves, but at much slower speeds because of scattering. The main cause of phonon-phonon scattering is due to what is called the anharmonicity of the forces in the crystal—that is, the nonlinearity of the restoring force on an atom as a function of its displacement from its equilibrium position. This means that the reaction of the lattice to a phonon will depend on whether another phonon is also passing through at the same time.

The remaining type of imperfection concerned with acoustic attenuation is the free electron. The free electron represents a singularity in the crystalline electric field which may perceptibly distort the lattice in the vicinity. Free electrons were originally represented as particles in the Drude-Lorentz theory, which, although now replaced by a quantum mechanical picture, is still useful in giving a more easily envisaged model of conduction. Electrons interact with phonons, impurities, and lattice defects, so that at room temperature the electron "mean free path" or distance between collisions is of the order of 10^{-6} centimeter, while at low temperatures this increases by a factor of 10^3 to 10^4.

Measurement of Attenuation

Before we consider the mechanisms by which these defects contribute to a loss of acoustic energy in a solid, let us discuss the quantities which are used to provide a measure of the attenuation.

When a solid is set in mechanical vibration, some of the elastic energy is always converted into heat, the mechanisms by which this takes place being collectively called "internal friction." Thus, when a solid specimen vibrates, its free oscillations decay even when it is isolated from its environment.

The most direct way of defining internal friction is as the ratio of the energy dissipated in taking the specimen through a stress cycle to the elastic energy stored in the specimen when the strain is a maximum. This ratio, $\Delta W/W$, is called the "specific loss." The value of specific loss is often found to depend on the amplitude and frequency of the applied stress and is always modified by the temperature and past history of the specimen. If the forces which restore the deformation are proportional to the amplitude of vibration and if the dissipative forces are proportional to the velocity of deformation, conditions which often apply, then the ratio between successive free oscillations of the specimen is constant and the natural logarithm of this ratio—that is, the logarithmic decrement—is constant and may be taken as a measure of the internal friction.

Another, less direct, measure of internal friction is given by the sharpness of the resonance curve under conditions of forced oscillation. If a specimen is driven by a force of fixed amplitude and variable frequency, and if the amplitude of vibration of the specimen is plotted against frequency, the curve shows a maximum close to the resonant frequency f and falls off on either side of it. The lower the internal friction, the sharper this resonance peak is found to be, and if Δf is the change in the impressed frequency necessary to change the amplitude from half its maximum value on one side to half its maximum value on the other, then $\Delta f/f$ is also a measure of the internal friction. The ratio $\Delta f/f$ for low damping is equal to $\sqrt{3}/2\pi$ times the specific loss. By analogy with the electrical resonance case, a quantity Q, the "quality factor" in engineering terminology, is sometimes used as a measure of the sharpness of the resonance curve. The relationships between the quantities mentioned so far are

$$\frac{1}{Q} = \frac{\Delta}{\pi} = 2\pi \Big| \frac{\Delta W}{W}$$

These methods of specifying the internal friction apply most naturally to experimental techniques in which the solid specimen is made to oscillate at or near its natural frequency—that is, with the acoustic wavelength of the same order of magnitude as the specimen dimension. The longitudinal and shear velocities of sound in most solids are of the order of 10^5 centimeters per second. The fundamental frequencies will therefore generally be of the order of 10^5 per dimension—that is, about 10^4 cycles per second. Prior to about 1946, most ultrasonic measurements on solids were carried out at such frequencies.

Since the development of radar techniques during World War II, however, measurements of the attenuation of sound in solids can now be made by a

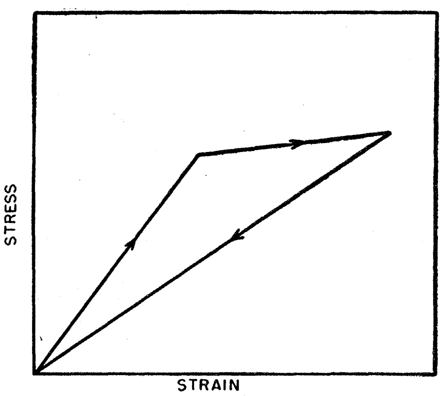

Fig. 4. A stress-strain hysteresis loop giving rise to "anelastic" behavior. The area of the loop represents the energy lost per half cycle by internal friction. This energy is dissipated as heat.

pulse technique. In this method, a pulse of sound, which may be at as high a frequency as 1000 megacycles per second, is injected into the solid specimen by means of a piezoelectric transducer which converts from electrical to mechanical oscillations. After passage through the specimen the acoustic pulse may be again reconverted to an electrical one and viewed on the cathode-ray oscilloscope. The ratio of the amplitude of the emerging pulse to that of the incident pulse gives a measure of the acoustic attenuation in the solid. With such techniques it is common to quote the loss in decibels (db). Thus

$$\text{db/cm} = 20 \log_{10} A_1/A_2$$

where A_1 and A_2 are the pulse amplitudes before and after passage of 1 centimeter through the solid material. The loss in decibels per centimeter can be related to the other measures of internal friction mentioned previously, since

$$\frac{1}{Q} = \frac{2\ (\text{db/cm})\ (\text{sound velocity})}{8.6\ (\text{frequency})}$$

In the remainder of this article I consider the three principal mechanisms by which ultrasonic sound is dissipated in solids and refer to some examples of these mechanisms which have been under recent study.

Ultrasonic Attenuation by Scattering

The scattering of sound in gases by objects whose diameter is less than the wavelength of the sound was studied in 1894 by Lord Rayleigh (*6*). He deduced the law of scattering to be such that the intensity of the scattered sound is inversely proportional to the fourth power of the wavelength. This law is also well known in optics, where light waves are scattered by small particles in the air. It is sometimes also noticed, for example, that the pitch of the echoes returning from, say, a group of trees appears to be raised above the pitch of the incident call. Since the sound in this case is complex, consisting, for example, of a fundamental tone plus a series of higher harmonics, the component tones will be reflected or "scattered" from the trees in increasing proportion toward the higher harmonics.

Similar effects cause the loss of intensity of high-frequency sound propagated through a polycrystalline solid when the wavelength of the sound is greater than a few times the diameter of the individual crystallites. Neighboring grains are, of course, at different orientations, and the elastic properties of crystalline materials are in most cases markedly anisotropic. As a consequence, a sound wave passing from one grain to the next will encounter a change in elastic medium and will be reflected. In the terminology of the electrical engineer, this is an impedance mismatch. The ultrasonic wave is accordingly attenuated, the attenuation being greater in more anisotropic materials. Mason and McSkimin (*7*) have shown that if the wavelength is more than about three times the grain size in aluminum, then the attenuation is inversely proportional to the fourth power of the wavelength, as in Rayleigh scattering. From the characteristics of the scattering process it is sometimes possible to obtain a measure of the size of the scattering particles, and it has been suggested by Roderick and Truell (*8*) that the method may be of use in metallographic examination. This process sets a limit to the usefulness of metals as ultrasonic delay lines at high frequencies. Figure 3 shows the experimental work of Mason and McSkimin (*7*).

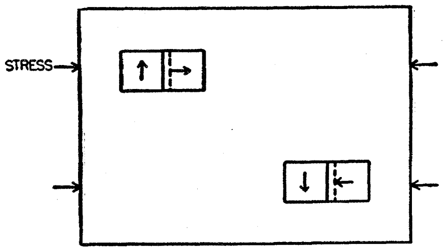

Fig. 5. The effect of compressive stresses on positive magnetostrictive or electrostrictive materials. The arrows inside the two pairs of adjacent domains show the directions of polarization within the grains. Stresses have little effect on domain walls parallel to them but enable perpendicularly polarized domains to grow. The new positions, under stress, of the domain walls are shown by the dashed lines.

Hysteretic Ultrasonic Attenuation

The truth of Hooke's law, *"ut pondus sic extensio"*—that is, the stress applied to a material leads to a proportional strain or deformation—has been widely challenged in recent years with the introduction of more refined measuring techniques. The subject of elasticity, which evolves from the assumed truth of this law, is still, however, of great importance. The deductions are sufficiently good approximations for most work of a technological nature, although interesting departures have recently been successfully made in building construction. The laws of elasticity still serve, and will probably always serve, as mathematical models against which the actual behavior of materials can be judged.

Except, however, at very small stresses, the strain in most solids is not a single-valued function of the stress applied. The strain does not follow the same path when the stress is reduced from a certain value as it does when the stress is increased from zero. A stress-strain hysteresis loop is formed, and the area of the loop represents mechanical energy which has been lost in the form of heat. This is known as "anelastic" behavior; development of the subject owes much to the work of Clarence Zener (*9*). Figure 4 shows a possible stress-strain cycle.

A number of recent investigations of acoustic loss in solids have revealed hysteretic mechanisms. One important class of phenomena of this nature is the amplitude-dependent loss in ferromagnetic and ferroelectric materials. These solids are respectively characterized by "domains" or regions in which the magnetic and electric polarization is in a single direction. If a ferromagnetic or ferroelectric material is placed in either a magnetic or an electric field, then the increase in over-all polarization is brought about by the growth of domains oriented in the direction of the field, at the expense of other domains less favorably oriented. A certain level of field energy is necessary to move the domain wall, and hence if the field is cycled, the field polarization rela-

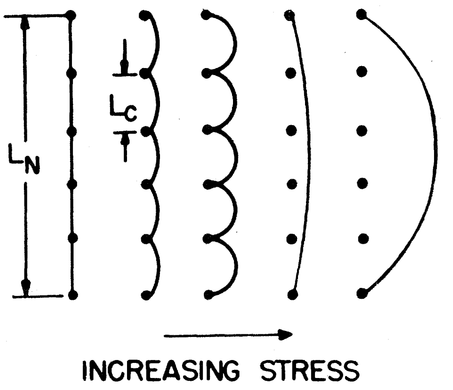

Fig. 6. The successive drawings indicate schematically the bowing out of a pinned dislocation line by an increasing applied stress. The length of loop determined by impurity pinning is denoted by L_c, and that determined by the net work, by L_N. As the stress increases, the loops L_c bow out until breakaway occurs.

tionship is in the form of a loop. The area of the loop represents the energy expended in polarization.

Such changes in polarization are accompanied, because of magnetostriction or electrostriction, by changes in the separation of atoms in the domain. Conversely, when a stress is applied to a ferromagnetic or ferroelectric material, a change in polarization of the domains is brought about. It turns out that domains which are polarized at right angles to the stress tend to grow at the expense of others not so directed. These changes are shown in Fig. 5. The hysteresis loss is dependent on the amplitude of the applied stress and should be independent of the frequency for cyclic stresses up to a limit when the domain wall is unable to move fast enough to follow the stress. The attenuation due to the hysteresis loss should then disappear.

Another type of hysteresis loss which is not yet fully understood, and which is under study in a number of laboratories, is concerned with the motion under cyclic stresses of dislocations in solids. For strain amplitudes of up to about 10^{-4} and at frequencies usually of the order of 10^4 cycles per second, it has generally been found that the internal friction in metals at room temperature and lower is, in accord with a hysteretic mechanism, frequency-independent and that it increases monotonically with stress. At stress levels beyond which dislocations increase rapidly in number, the internal friction rises sharply.

There has been much speculation about the mechanism which accounts for the internal friction at low amplitudes and at temperatures at and below room temperature (*10*). The model which appears to be most successful is that proposed by Granato and Lücke (*11*), shown in Fig. 6.

The single metallic crystal is assumed to contain a network of dislocations, with the network locking points strong enough to resist breakaway under stresses within the hysteretic loss range. The dislocations are further pinned by impurities. It can be seen from the structure of an edge dislocation (Fig. 1) that hydrostatic stresses around the dislocation may be relieved by a suitable arrangement of nearby solute atoms. Assuming therefore, that the necessary diffusion of impurities is possible, we can postulate that each dislocation gathers round itself an "atmosphere" of solute atoms. At a particular temperature, therefore, we have a typical dislocation length locked at its ends firmly enough to resist the stress applied and less firmly pinned at intermediate points by impurity atoms. As the stress is increased, the dislocation bows out as shown, and deformation strain occurs. At a particular value of stress the loop breaks from an impurity pin and the consequently enlarged loop then tears away from the remaining impurity pins until the network length is reached. At this point the strain increases with little extra stress. The return part of the cycle, with the stresses being reduced, causes the dislocation to collapse until pinned again by the impurities. A stress-strain hysteresis loop similar to that shown in Fig. 4 is thus formed, and the energy lost to heat per cycle is again equal to the area of the loop.

The inherent difficulties in this model, which has had general success, lie in the mechanism of loss due to dislocations which are initially not pinned by impurities and in the choice of distribution function of dislocation loop lengths. A pinning point which resists the greatest stress applied at one temperature may of course be weakened sufficiently to break at a higher temperature. This modification and the detail of the nature of the loss once the pins have broken have been studied by Rogers and Hutchison (*12*).

Relaxation-Type Ultrasonic Attenuation

I shall now discuss the third and perhaps the most important class of mechanism which gives rise to acoustic attenuation in solids. In this class the solid is regarded as a system which, when subjected to a sudden stress, relaxes that stress at a characteristic rate. The rate depends on the specific nature of the relaxation process and invariably involves the transfer from one configuration to another of some internal imperfection of the solid lattice. Relaxation processes are associated with each of the imperfections discussed above. Specific models can be set up for each of the processes, such as relaxation by stress-induced interstitial diffusion, relaxation by dislocation motion, and so on. On the other hand, a good introduction to the subject can be made by setting up a general phenomenological model and deducing the basic nature of relaxation damping. To set up a detailed model for a specific process is then more meaningful. This is the plan

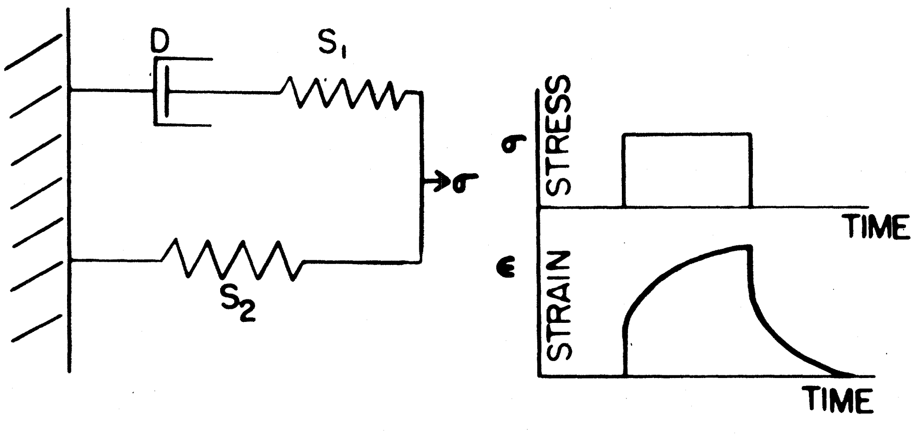

Fig. 7. The "standard linear solid." S_1 and S_2 are springs, while D is a dashpot arrangement. The diagram at upper right shows a stress σ which, when applied to the standard linear solid, produces the subsequent displacement or strain ϵ shown in the diagram at lower right.

I follow in the remainder of this article.

The most generally successful mechanical model which has been proposed to simulate the stress-strain behavior of real solids is that proposed by Zener (*9*). It is called the "standard linear solid" and is shown in Fig. 7. The model consists of the parallel arrangement of spring S_2 and spring S_1-dashpot *D*.

Suppose a stress σ is suddenly applied; then the system will have an instantaneous displacement or strain ϵ, depending solely on the spring constants. If, however, the stress is maintained, then the dashpot relaxes, increasing the over-all strain. Conversely, when the stress is suddenly removed, the springs will release some of their stored energy and this will result in a partial instantaneous recovery. The complete release of all the energy in the springs must await the gradual relaxation of stress across the dashpot. The general features of elastic aftereffects in real solids are thus given by the model, in which both the strain and rate of strain are dependent on the stress and rate of stress.

It may now be of interest to the reader with a background in the mathematical sciences or in engineering to actually work out the solution of the differential equation which expresses the strain and rate of strain as a function of the stress and rate of stress. The method used is of wide application in electrical engineering.

If σ, $\dot{\sigma}$, ϵ, and $\dot{\epsilon}$ are the stress, rate of change of stress, strain, and rate of change of strain, respectively, then the behavior of the standard linear solid is given by the equation

$$\sigma + \tau_\epsilon \dot{\sigma} = C(\epsilon + \tau_\sigma \dot{\epsilon}) \qquad (1)$$

where C, τ_ϵ, and τ_σ are constants.

The nature of τ_ϵ and τ_σ is shown by making, for example, a test of the equation under conditions of constant strain. Let us say that $\epsilon = 0$. Then Eq. 1 reduces immediately to

$$\sigma + \tau_\epsilon \dot{\sigma} = 0$$

The solution of this simpler equation is $\sigma = \sigma_0 e^{-t/\tau_\epsilon}$ where t is time.

Hence τ_ϵ is the time which elapses between a stress value of σ_0 and a stress value of σ where $\sigma_0 = \sigma \times e$. In other words, τ_ϵ is the time constant of the circuit for constant strain. Likewise, τ_σ is the time constant of the circuit for constant stress.

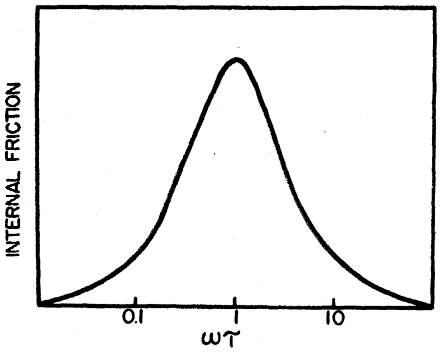

Fig. 8. Variation of internal friction with $\omega\tau$ for a relaxation process when ω is the applied stress frequency and τ, the time of relaxation of the process. The maximum at $\omega\tau$ equal to unity is characteristic of a relaxation process.

Suppose the stress and strain are both periodic, as they are in most experimental determinations of internal friction. Let us substitute the periodic solutions $\sigma(t) = \sigma_0 e^{i\omega t}$ and $\epsilon(t) = \epsilon_0 e^{i\omega t}$, where ω is the applied angular frequency. Then Eq. 1 becomes

$$\sigma_0(1 + i\omega\tau_\epsilon) = C(1 + i\omega\tau_\sigma)\epsilon_0$$

The value of stress/strain or the "impedance" Z is now

$$C(1 + i\omega\tau_\sigma)/(1 + i\omega\tau_\epsilon)$$

Finally, the dissipation loss $1/Q$ (internal friction) is given by

$$\frac{\text{imaginary part of } Z}{\text{real part of } Z}$$

That is,

$$\frac{1}{Q} = \frac{\omega(\tau_\sigma - \tau_\epsilon)}{1 + \omega^2\tau_\sigma\tau_\epsilon}$$

or

$$\frac{1}{Q} = (\text{approx. constant}) \left(\frac{\omega\tau}{1 + \omega^2\tau^2}\right) \qquad (2)$$

where τ is the geometric mean between τ_σ and τ_ϵ.

Let us now see how the internal friction $1/Q$ varies with the angular frequency ω for different values of relaxation time. The $1/Q$ versus $\omega\tau$ relation of Eq. 2 is drawn in Fig. 8. The internal friction maximum, at a value of $\omega\tau$ equal to unity, shows an important characteristic of a relaxation mechanism which makes it amenable to test by ultrasonic techniques. If the angular frequency of the applied stress in the experiment equals the inverse of the relaxation time of the system to which the stress is applied, then the system absorbs the maximum amount of acoustic energy, the dissipation loss falling off sharply with frequency above and below the critical value.

Many relaxation systems exist in solids. Their study by acoustic attenuation experiments has been most fruitful in obtaining information about the internal structure and modes of relaxation of the solid itself.

Let us choose as our first example the nature of thermoelastic losses in polycrystalline metal specimens; this is easy to understand in general terms and will serve as introductory relaxation theory for those readers who did not care to read the mathematical analysis.

When a crystal is stressed suddenly its temperature changes, the temperature of the parts of the crystal under compression being raised and of those under tension being lowered. Since the stresses in polycrystals are not uniform but vary from grain to grain, it follows that in these the temperature resulting from this thermoelastic effect also varies from grain to grain. Now, if the stresses vary slowly as compared with the time required for heat to flow between regions having different temperatures, the temperature remains constant and the transfer of mechanical energy into heat, and vice versa, takes place reversibly. There is then no contribution to the internal friction. Similarly, if the vibrations in stress take place so rapidly that no heat flows during a stress cycle, the process occurs adiabatically, for every grain behaves as if it were thermally isolated. It follows that the net conversion of elastic energy into heat during a complete cycle is also zero in this case. At intermediate frequencies there is a finite contribution to the internal friction from the thermoelastic effect.

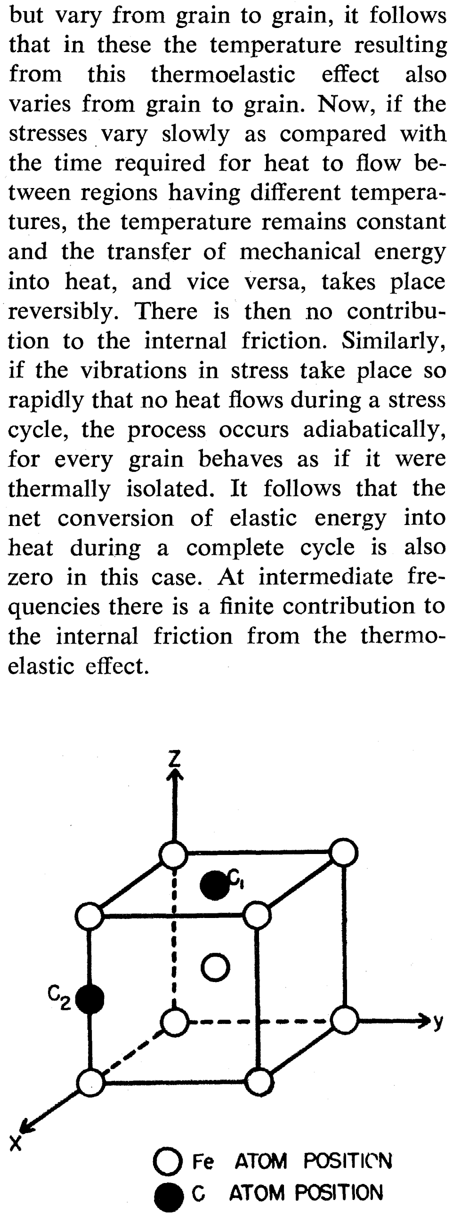

Fig. 9. Unit cell of body-centered cubic iron. When the cell is elongated by stress in the Z direction, the favored positions for interstitial carbon atoms are C_1 and C_2.

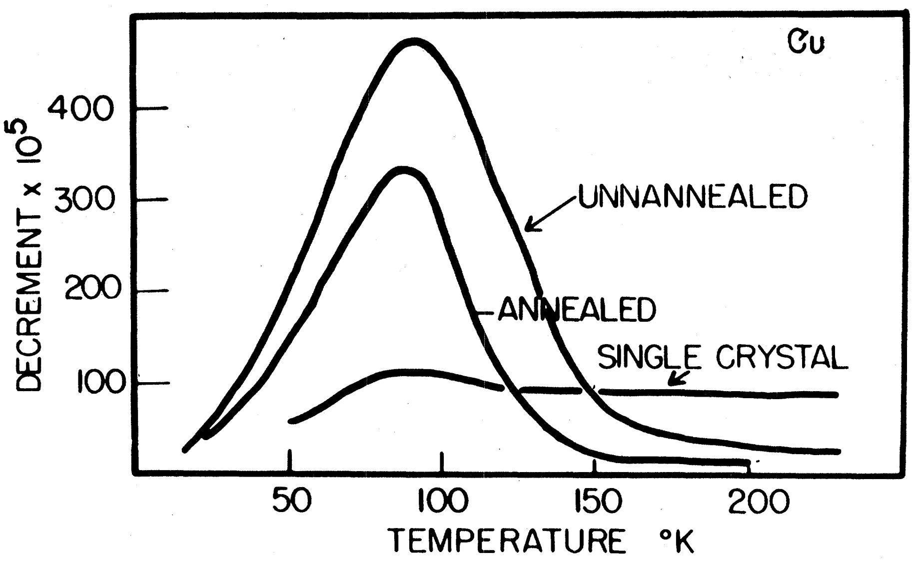

Fig. 10. The Bordoni internal friction peak in copper at a frequency of applied stress of 30 kilocycles per second. A reduction of the degree of cold working of the specimen (by annealing) also reduces the height of the attenuation maximum but does not alter the temperature at which it occurs.

Zener, in his discussion of this problem (*9*), showed that the thermoelastic contribution to the decrement Δ is given by three factors,

$$\Delta = R \cdot \Delta_E \cdot \Omega$$

The factor *R* depends on the anisotropy of the grains and is greater for the noncubic metals. The factor Δ_E is called the relaxation strength and contains the plausible quantities, compressibility, thermal expansion coefficient, specific heat, and temperature. The frequency factor Ω equals $\omega\tau/(1+\omega^2\tau^2)$ where ω is the applied angular frequency of the stress and τ is the time for heat to flow at the temperature of the specimen across neighboring grain boundaries. The variation with frequency of the thermoelastic damping will therefore be of the form shown in Fig. 8. Naturally τ contains the grain size and the rate of diffusion of heat. The correctness of this interpretation of damping maxima found in brass specimens of different grain sizes was quantitatively confirmed by Randall, Rose, and Zener (*13*) when they correctly deduced the grain sizes from the frequencies of maximum attenuation.

Measurements of internal friction have also been of great importance in the investigation of the motions of interstitial and substitutional impurity atoms. Much of the theoretical development of the subject is again due to Zener, while detailed systems have been studied by Snoek (*14*) and Dijkstra (*15*).

Let us examine the motion under thermal activation of carbon and nitrogen atoms in body-centered iron. The interstitial positions which these atoms occupy are the face centers and mid-points of the edges of the body-centered cubic cell. Such positions are midway between the iron atoms. Since the lattice is cubic, all of the face centers and edge mid-points are equally favored, and equilibrium between the positions is established by thermal agitation. Suppose, however, that a stress is applied to the cell in the *Z* direction (see Fig. 9) which causes the iron atoms to move further apart along that axis. The favored positions for the carbon or nitrogen interstitial atoms will then be positions such as C_1 and C_2. In order to move to C_1 and C_2, the interstitial carbon or nitrogen atoms must have thermal energy imparted to them equal to the activation energy for the change in position. The average time τ that elapses between jumps for a specific carbon atom is given by the Arrhenius type equation

$$\tau = \tau_0 e^{18,000/RT}$$

where τ_0 equals 0.45×10^{-13} second, *R* is the gas constant (= 2 calories per mole per °K) and 18,000 calories per mole is the activation energy for the carbon jump. At a temperature of 300°K we have, therefore, τ equal to about 0.5 second.

Observations of the internal friction in steel wires, in slow-oscillation experiments with periods of about 0.5 second, should, therefore, disclose the relaxation damping due to the motion of the interstitial carbon atoms.

It is obvious that the attenuation at a fixed frequency will fall off rapidly as the temperature is decreased or increased from the value where the damping is a maximum. Suppose, for instance, that the temperature is raised in the steel specimen by 50°K while the period of oscillation remains about 0.5 second. Then τ has the new value of 0.005 second, and the value of the internal friction, as determined from a consideration of the frequency factor discussed above, would fall to about 2 percent of its value at 300°K.

A further simple calculation also shows that raising the temperature at which the experiment is conducted from 300° to about 450°K and above would bring the search for the attenuation maximum into the ultrasonic region.

There are many such relaxation processes in nature, with the reordering of the solid taking place under thermal action and obeying an Arrhenius-type law, as in Eq. 3. Stress relaxations are caused by slip at grain boundaries, slip at twin boundaries, reorientation of pairs of solute atoms, reorientation of point defects, molecular motions in polymers, and so on.

An interesting use of the technique of following the mobility of interstitial atoms in steels by attenuation measurements has been made by Harper (*16*). He was concerned with the study of a phenomenon known as strain aging, in which a steel that has been allowed to age for various periods of time at room temperature acquires a degree of brittleness which renders it useless for stamping operations. As one can imagine, the havoc wrought in the raw-material logistics of many industries has made the study one of major technological importance.

Harper was testing a theory of the strain-aging process developed by Nabarro, Cottrell, and Bilby (*17*), in which they regarded the process as one in which solute atoms migrate towards free dislocations at rest in an overstrained crystal and anchor the dislocations by forming atmospheres. The dislocation slip process is then inhibited, and the material becomes brittle. Harper used internal friction measurements, similar to those described above, to determine the amount of carbon remaining in random solution—that is, not settled on dislocations. He made this

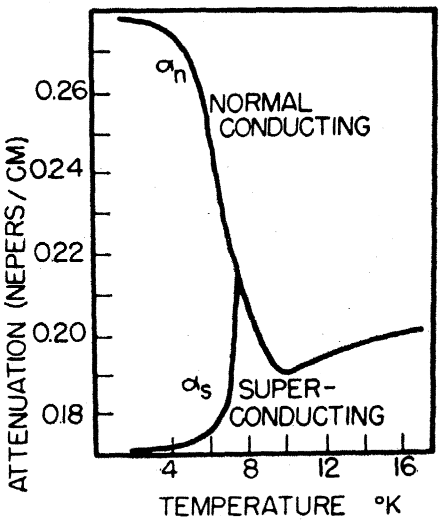

Fig. 11. The increase at low temperatures of the attenuation of sound of high frequency. The applied frequency is here 26.5 megacycles per second; the specimen is fairly pure lead. Below about 7°K the lead becomes super-conducting and the attenuation falls rapidly (α_s). The normal conducting state may be restored below 7°K by a magnetic field, and the attenuation values α_n obtained.

determination after aging the steel for different times at different temperatures and was able to confirm the predictions of the rate at which strain aging takes place.

It is not too surprising that a serious search for relaxations in solids by measurements of acoustic attenuation had not been extended to low temperatures until quite recently. It was believed that the internal friction fell off with temperature and approached zero at 0°K. This is in general true. As the lattice energy falls off quite rapidly below about one-third of the Debye temperature (see Fig. 2), it was not expected that relaxation processes, which in general are thermally activated, would appear at low temperatures.

However, in 1954 Bordoni (*18*) reported measurements of the internal friction of several metals at frequencies of about 40,000 cycles per second and at temperatures from 4°K up to room temperature. He found a large absorption peak at temperatures around 100°K; for copper, for example, at 30.3 kilocycles per second, the peak temperature was 90°K. The height, but not the position, of the peak was increased by small amounts of plastic deformation of the specimen. Annealing at high temperatures reduced the magnitude of the attenuation maximum. Figure 10 shows a plot of internal friction against temperature for copper in various conditions. Other measurements (*19*) at different frequencies have shown that the peaks are relaxation peaks, since the frequency and peak temperatures are related by an equation of the type of Eq. 3. The activation energy is low, being about 2000 calories per mole for the different metals.

Mason (*20*) at first believed that dislocation loops, whose lengths were defined by the distance between points where the dislocation was pinned by impurity or structural defects, were oscillating under thermal agitation at a definite rate. When the frequency of the applied stress matched this rate, then the relaxation internal friction would be a maximum, as discussed above. The temperature of the damping maximum was, however, shown to be independent of the amount of plastic deformation and impurity content and condition. Since such changes would certainly vary the loop length between locking points, Mason's theory appeared to be untenable. Seegar (*21*) has proposed an important modification of the Mason model, in which it is suggested that only portions of the dislocation loops, known as "kinks," move under thermal influence and so account for the relaxation process. The relaxation temperature is thus a characteristic of the dislocation itself and is independent of the nature and number of the impurity or structural locking points.

The dislocation relaxation mechanisms are not confined to metals but have also been found in natural and synthetic quartz, the wide use of the latter as crystal oscillators making the phenomenon one of technological concern.

The use of high-frequency pulse techniques for measurement of ultrasonic attenuation has recently revealed an entirely new kind of damping in metals at low temperatures. This is due to an interaction between the lattice, which is oscillated with the sound wave, and the conduction electrons of the metal. At very low temperatures, let us say at 1°K, the "mean free path" of the electrons has increased to perhaps 10^4 times its value at room temperature and may be up to about half a millimeter in very pure materials. Since the velocity of sound in metals is about 5×10^5 centimeters per second, the mean free path in such pure metals would equal the acoustic wavelength at a frequency of about 10 megacycles per second. Equipment is now readily available to study attenuation with acoustic wavelengths greater than and less than the electronic mean free path.

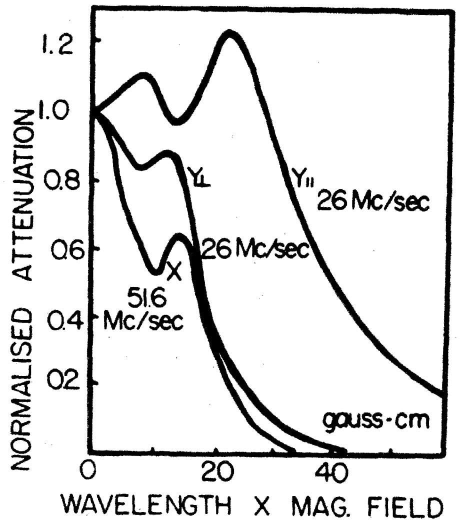

Fig. 12. The variation at liquid helium temperatures of normalized acoustic attenuation in pure copper is shown plotted against the product of wavelength and magnetic field. *X* denotes longitudinal waves and $Y_\perp$, shear waves with the magnetic field perpendicular to both the direction of the wave and the plane of polarization, while $Y_{\parallel}$ had the magnetic field in the direction of the polarization vector. Maxima and minima of attenuation occur for certain coincidences of electron orbit diameter and acoustic wavelength.

Bömmel (*22*) and, independently, MacKinnon (*23*) first discovered that the ultrasonic attenuation increases at very low temperatures. Bömmel's results for lead are shown in Fig. 11. It is probable that the acoustic wavelength in this work was greater than the electronic mean free path, since the lead was not of the highest purity. The attenuation has been shown for this condition to be proportional to the mean free path and, consequently, to the electrical conductivity, and also to vary as the square of the applied frequency. While Mason (*24*) has proposed a theory that the attenuation is due to a transfer of momentum from the lattice to the electron gas and a subsequent damping due to the viscosity of the gas, it is possible to regard the process as a relaxation mechanism. Morse (*25*) and Kittel (*26*) believe that a more general description of the mechanism is that of distortion of the momentum pattern of the electrons by the sound wave, this distortion then relaxing by collision of the electrons with the phonons present. The relaxation time is similar to that involved in the process of electrical conductivity. An analysis, which is similar in form to that given above for a relaxation mechanism, then leads to a relationship between attenuation, frequency, and conductivity which, in the lower limit of $2\pi l/\lambda < 1$ is similar to Mason's. Here λ is the acoustic wavelength and l, the mean free path.

Extremely interesting experimental results have been recently found for the case when the mean free path of the electrons is greater that the acoustic wavelength—that is, $2\pi l/\lambda > 1$—a condition which is brought about by using very pure metals and high frequencies. Some of the results are reproduced in Fig. 12, taken from a paper by Morse, Bohm, and Gavenda (*27*).

It may be seen that the application of increasing magnetic fields to the specimen causes the lattice electron attenuation to oscillate in value. Here the conduction electrons, having long paths, are spiraled round by the magnetic field, and it appears that maxima and minima of attenuation occur for certain coincidences of the electronic orbit diameter and the wavelength.

Another interesting feature of lattice-electron attenuation is apparent from a study of Fig. 11. Below about 7°K the attenuation α_s is seen to fall off very steeply. This occurs at the transition temperature below which lead becomes super-conducting. It is possible to restore the normal conducting state at temperatures below the transition temperature by the application to the specimen of a magnetic field greater than a certain value (*28*). The attenuation rises as a consequence of the metal becoming normal (α_n in Fig. 11), the experimental method thus providing a tool for the study of the phenomenon of superconductivity. Several papers have appeared (*29*) recently in this latter connection, as a result of the recent success of Bardeen, Cooper, and Schrieffer (*30*) in their theoretical attempt to explain superconductivity, a problem which has been extant for some fifty years.

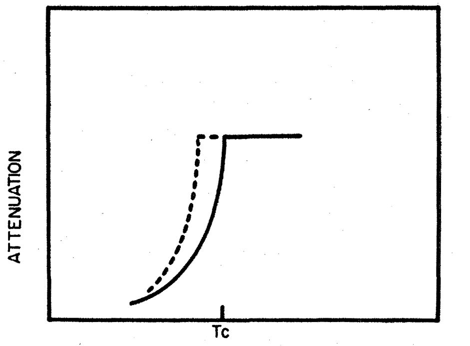

Fig. 13. The expected variation of kilomegacycle frequencies of acoustic attenuation with temperature for a superconductor. Morse has proposed that when $h\nu$ becomes of the order of kT (see text), electron transitions may be induced across an energy gap which, according to Bardeen-Cooper-Schrieffer theory, appears at the transition temperature. The metal specimen would then appear to be normal-conducting to lower temperatures (dotted line) than would be the case at lower frequencies (solid line), when such transitions are impossible.

Table 1. Typical magnitudes for energy associated with very high frequency elastic waves; kT at $1°\mathrm{K} = 8 \times 10^{-5}$ electron volts.

Frequency (Mcy/sec)	Wavelength (cm)	Energy E (electron volts)
100	3×10^{-3}	4×10^{-7}
1,000	3×10^{-4}	4×10^{-6}
10,000	3×10^{-5}	4×10^{-5}

A great difficulty in this work is to know the magnitude of the experimental "background" loss which must be subtracted from the attenuation due to the conduction electrons. This has reduced the value of much of the high-frequency work as a quantitative test for the different theories.

It may be of interest to mention in conclusion an experimental test of the Bardeen-Cooper-Schrieffer theory which should be relatively free from this defect and which at the same time points the way to future ultrasonic research in solids (*31*).

Let us first examine the magnitudes of the energy associated with very high frequency elastic waves. The energy E is given, as for phonons, by $E = h\nu$. Many transitions of electron energy in solid-state physics have been discovered which become possible when the energy E is of the order of kT where T is, as before, the Kelvin temperature and $k = 1.38 \times 10^{-23}$ joule/°K. We have already seen the ratio E/kT appear in the "probability factor" (E/kT) of the Arrhenius equation (Eq. 3). It is perhaps surprising to realize that, with the advent of very high frequency acoustic waves in solids, the value of $h\nu$ is now approaching kT for the attainable low temperatures of 1°K and below. Some typical magnitudes are shown Table 1, taken from Morse (*30*).

Normally, electrons have a continuous range of energy values in a metal up to a value known as the Fermi level. There are available energy levels above this value which are normally unfilled. The imposition of an electric field or an acoustic wave can thus transfer energy to the electrons which go partially into the previously unfilled band. Now it is a central feature of the Bardeen-Cooper-Schrieffer theory of superconductivity that around the Fermi level a gap of nonavailable energy levels appears. This gap is of the order of kT in magnitude and increases in width as the temperature falls below the superconducting transition temperature (Tc).

To return now to the experimental test of the theory, it now seems possible at high enough acoustic frequencies to induce electron transitions directly across this gap. The metal would therefore appear to be normal below the transition temperature, and attenuation values would follow the dotted line in Fig. 13. The value of the new temperature at which the attenuation falls discontinuously would also be relatively free from the indeterminate background loss, and the whole experiment, although difficult to perform, should yield quantitative results.

This is merely one of the many experiments which underline the importance of an extension of ultrasonic research into the kilomegacycle region and above. There is no doubt that when directed "phonons" of wavelength short enough to be associated with the phenomena of "thermal conductivity" become available, there will be an exciting harvest to be reaped.

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New Frontiers to Health in Africa

The creation of new, independent states in Africa poses new problems in the eradication of disease.

K. R. S. Morris

Those of us who are working in Africa are being confronted today by a disturbing reversal of the past half century's fine record of progress in the conquest of disease in that continent. The cause lies in the petty nationalisms now arising in new African states. That the effects may be serious, not only for the new countries but for territories far outside their boundaries, can be seen from the example of sleeping sickness.

Epidemics and Their Control

This disease, caused by the protozoan *Trypanosoma gambiense* and carried from man to man by the riverine tsetse flies, *Glossina palpalis* R.D. and *G. tachinoides* West, has been present in West Africa for 600 years (*1*) but only developed into widespread epidemics after 1920, although in East Africa catastrophic outbreaks had occurred in several places just after the turn of the century. These East African outbreaks were due to the introduction of infections from the Congo by travelers and slavers; I have traced (*2*) the spread of a series of epidemics from west to east across Uganda, each following a big population movement. The West African epidemics, greater both in extent and intensity than those of Uganda and Kenya, also followed big expansions in travel, commerce, and agriculture, which accompanied British and French colonization. By 1940, when the epidemics everywhere had reached their peak, there was severe depopulation of large areas, particularly in some of the most fertile and well-watered river valleys of the Volta and Niger systems (*3*). West Africa could ill afford nonproductivity in this territory, since in neighboring, unaffected areas the population was increasing by 10 to 15 percent in a decade and was starting to feel the effects of soil erosion and its associated evils.

This grave situation was tackled in slightly different ways by the governments of various colonial territories, with the French well in the lead, both regarding the scale of operation and the logic and thoroughness of application. The fact that the French had in French West Africa a uniformly administered territory, stretching from Dakar to Niamy on the Niger, made possible such a wide approach, but it took the vision and tenacity of Médecin Général Muraz to make this a reality by creating an autonomous "Service de la Maladie du Sommeil" in 1939, to deal with the whole of French West Africa according to a uniform plan, and the realism of Dr. Jamot to devise a method (mass survey and treatment with mobile bush teams of local natives) which would be effective against such a huge and dynamic problem (*4*). Moreover, Muraz recognized a pattern in the several epidemic areas, placed the headquarters of the Service at Bobo Dioulasso, in the heart of the largest of them, and divided the whole country into sectors of three grades—heavily, lightly, and very lightly infected—so that the degree of attack could be commensurate with the severity of the problem. The emphasis was heavily weighted on the side of chemotherapy, with tsetse fly control as a secondary measure.

In the Gold Coast, affected in the northern part by the huge Volta epidemic, emphasis was placed on vector control, since a method for the complete eradication of *Glossina palpalis* and *G. tachinoides* by selective clearing had been developed there (*5*). In 1940 and 1944, French entomologists visited the Gold Coast to learn this technique, which was then applied in the neighboring territories of the Ivory Coast and Upper Volta. Thus, in French West Africa, with the severely infected areas receiving three to four visits from the survey teams per year and with very thorough treatment and follow-up of patients, the French got their epidemics almost completely under control by 1945, the degree of control being greatest in the heavily infected savanna country of the hinterland, where "le selective clearing" had been most effectively applied, and least toward and in the more lightly infected rain-forest zone nearer the coast, where tsetse control was too difficult to be attempted. The French then introduced mass prophylaxis with lomadine, to deal with the

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