CORNELL AERONAUTICAL LABORATORY, INC.
Buffalo 21, New York
APPLIED PHYSICS DEPARTMENT

File: C35-001
October 11, 1961
JDM:js-14

To: Godfrey F. Buranich

From: John D. Myers

Subject: Energy Transfer Modes Adaptable to the Generation of Heat in Solids at Large Distances

This memorandum investigates the possible efficiences of energy transfer to solids over large distances with primary consideration given to heating effects.

Solids absorb energy mechanically in a mechanism whereby the relative position of the atoms with respect to their nearest neighbors is changed. This change in position can be either static or dynamic. A static change in position pertains to the compressibility of a material, and the energy absorbed is potential energy. A dynamic change in position pertains to the harmonic-oscillator nature of an individual atom of a solid and manifests itself as heat. The maximum energy that a solid can absorb and remain a solid corresponds to its binding energy. Any energy in excess of the binding energy which is absorbed by an atom will show up as the kinetic energy of that same atom after it is ejected from the material.

Consideration of the practical aspects involved in any applications of energy transfer in the realm of "action-at-a-distance" phenomena leads one to conclude that the best possible modes of this energy transfer lie in exploiting the harmonic oscillator nature of the atom.

A word should be said here about this harmonic oscillator and its absorption process. The harmonic oscillator absorbs energy by increasing the amplitude of its oscillation. This increase in amplitude corresponds to an increase in the temperature of the material. Thus, it follows that by sufficiently increasing the amplitude of the oscillation, one may bring about the vaporization of the material. The amplitude-increasing process is usually brought about by some bombarding agent such as electrons, ions, or other atoms, such that the kinetic energy of the bombarding particles is transferred to the harmonic oscillator. A simple example would be resistance heating where the conduction electrons in a metal, under the acceleration of a potential difference, are constantly bumping into the atomic lattice of the material and losing part of their kinetic energy to the lattice. However, the harmonic oscillator can absorb energy in another manner. There are available to a harmonic oscillator numerous energy states. Thus a harmonic oscillator can also absorb energy in discrete quanta ($h\nu$) and re-emit all or part of this energy. These quanta are analogous to an amount of discrete change in the amplitude of the harmonic oscillator. Again, if a quantum of energy absorbed is greater than the binding energy of the atom, the atom will leave the lattice with a net kinetic energy. This phenomenon is illustrated by the ejection of copper atoms from the lattice by incident X-ray radiation.

The efficiency of either of the above absorption processes is a function of the frequency of the incident radiation. For frequencies ranging from radio frequency to the infrared, the fraction of the incident energy truly absorbed (R_t) a.e., transformed into heat, is approximately equal to:

$$R_t \cong \frac{2\omega\delta}{C} \qquad \text{(For conductors)}$$

where: ω = frequency of incident radiation

C = velocity of light

δ = skin depth

The skin depth can be expressed as:

$$\delta = \left(\frac{\lambda_0 \sqrt{\kappa_0/\mu_0}}{\pi \mu \sigma} \right)^{1/2}$$

where λ_0 = vacuum wave length ($\frac{2\pi C}{\lambda}$)

κ_0 = propagation constant of free space

μ_0 = magnetic permitivity of free space

μ = magnetic permitivity of media

σ = electrical conductivity of media

Thus, for copper, for which $\delta = 3.82 \times 10^{-6} \sqrt{\lambda_0}$, only about 1 percent of the incident energy is absorbed for a wavelength of 1 cm. Using the expression for R_t we see that the rate at which energy enters the metal per unit area is:

$$\frac{dU}{dt} = \frac{2\omega\delta}{C} \cdot \mu_0 C H_i^2 \cong \frac{\omega\delta}{2} \mu_0 H_t^2 \; ^{(1)}$$

where: H_i = incident H vector

H_t = transmitted H vector.

Again using copper as an example, it follows that in order to vaporize 1 cm^3 of copper per second (energy density ≅ 400 joules per cm^3) we would need a beam with a power density of over 40,000 watts per cm^2 for a wavelength of approximately 1 cm.

As the frequency of the incident radiation approaches the optical region, the above equations no longer provide an accurate description of the absorption properties of materials. In the near infrared region, resonance absorption becomes appreciable and one must turn to thermodynamics to obtain adequate descriptions of the absorption of materials of radiation in the 1000 to 8000 angstrom range.

---

[1] Harnwell: Princ. of Elect. and Mag. p 587

In general, the fraction of incident isotropic radiation of all wavelengths that is absorbed depends on the temperature and the nature of the surface of the absorbing body. For example, polished metals will absorb anywhere from 3 to 40 percent of the incident radiation depending upon the metal used and its temperature. The actual percentage of incident energy absorbed by a material must be determined experimentally. The highest known absorbing material is lampblack, which absorbs 95 percent of the incident energy. However, it must be remembered that the above absorptivity values are actually average values taken over a wide range of frequencies. One can conceivably select monochromatic radiation corresponding to a much higher value of absorptivity for a given material than the average value. The radiation need not have an especially narrow bandwidth either, since absorption spectra of solids is made up of absorption bands rather than lines. For example, copper will absorb from 60 to 75 percent of incident radiation limited to wavelengths between 5000 and 2000 angstroms. This absorption of the major portion of incident green, blue, and violet light accounts for the characteristic redness of copper. This does not mean, however, that the net absorption of energy will remain at this level throughout the temperature range of the solid. At certain temperatures, the material will give off by thermal radiation a significant portion of the absorbed energy. But, even taking this into account, the net absorption of light will be greater than the net absorption of r.f. by a factor of ten.

Then, too, the light absorption process is not limited to metals. Consider the case of the ruby. The ruby has a strong absorption band in the green and characteristic fluorescence in the near infrared. The quantum efficiency of this process of absorption and emission is one. That is, for each photon absorbed in the green band, one photon is emitted in the red band. (Since the energy is not retained as heat this quantum efficiency corresponds to the <u>least</u> desirable case.) This particular absorption-emission process results in a net energy absorption of approximately 20 percent of the incident radiation. Thus in each of the above cases the required power density of an optical beam for removing 1 cm^3 of copper per second is of the order of 10^3 watts per cm^2. The absorptivity generally increases as the wavelength of the incident radiation approaches the X-ray region.

In the X-ray region, we must again resort to a "skin-depth" type procedure to describe absorption. The intensity of a monochromatic X-ray whose rays are parallel is reduced as the beam passes through an absorbing medium according to the exponential law,

$$I = I_o e^{-\mu d}$$

in which I is the intensity of the beam after passing through d centimeters of the material, I_o is the intensity of the original or incident beam and μ is the linear absorption coefficient. This linear coefficient of absorption is composed of two parts. One part (τ) represents the photoelectric or true absorption and the other part (σ) represents a scattering process. Thus

$$\mu = \tau + \sigma$$

Since, for our purposes, we are more interested in τ, we shall consider only the wavelength range from roughly 3 to 0.3 angstroms where the photoelectric type of absorption greatly exceeds that due to scattering. Very approximately, one may then say

$$\mu = \tau \cong c\, Z^4 \lambda^3$$

Where c is a constant characteristic of the absorbing material, Z is the atomic number, and λ is the wavelength of the incident radiation. This is known as Owen's law. Typical values for μ for wavelengths between 0.4 and 2.3 angstroms (L-radiation) are as follows:

For copper: $\mu = 91.5$ at $\lambda = .417$ A
$\mu = 246.2$ at $\lambda = .880$ A
$\mu = 621.0$ at $\lambda = 1.235$ A
$\mu = 171.5$ at $\lambda = 1.656$ A
$\mu = 413.1$ at $\lambda = 2.29$ A

(The dip in μ versus λ is an indication of the K absorption edge of copper.) It is seen from the tabulated absorption coefficients that the entire beam is absorbed within a short depth from the surface. However, all of the energy of this incident beam is not retained by the absorbing material as heat. A rather large portion is re-emitted as fluorescent or characteristic radiations. This fluorescent radiation may account for between 40 and 80 percent of the energy of the incident beam depending upon energy trapping characteristics of the absorber. Thus, the minimum amount of energy which will be absorbed as heat would be approximately 20 percent of the incident beam. Thus again, as in the case of light absorption, a beam of power density of the order 10^3 watts per square centimeter would be required to vaporize 1 square centimeter of material. Present X-ray beams are of the order of 10^{-2} watts per square centimeter.

The absorption properties of alpha, beta, and gamma radiation are similar to the absorption properties of X-rays. Penetration depths of alpha radiation is similar to extremely soft X-rays which are attenuated quite readily by the atmosphere. Beta radiation is similar in penetration depths to X-rays in the .1 to 10 angstrom range and gamma radiation approximates the penetration properties of the very hard X-rays. However, the energy per photon of alpha, beta, and gamma radiation is greater than that of X-ray radiation by a factor of 10^3. One main point of difference lies in the ability to focus alpha and beta radiation by means of electric or magnetic lenses. Otherwise, approximately the same absorption efficiencies apply along with the same problems in re-emitted energy from the absorber and present limitations in beam power densities.

A mention should be made here of the energy transfer by means of particle bombardment at energies of the order of the binding energies of the absorbing material. This subject includes such vehicles as ion and electron beams.

Ion beams have been investigated in relation to developing sputtering techniques. From the data collected, we can derive the following information. In order to be able to remove 1 cubic centimeter of material, an ion beam of approximately 10^2 watts per square centimeter would be required. Thus, the power density required by an ion beam to remove one cubic centimeter of material is less than that required by the best electromagnetic modes of transfer by a factor of 10. There is an important drawback in using an ion beam, however, which pertains to the large attenuation of such a beam by the atmosphere. The use of such a beam requires a high vacuum environment.

The use of electron beams would be still more efficient. Electron beam machining techniques now utilized in actual production operations have proved the practicality of such schemes. The amount of incident energy transferred into heat is almost 100 percent with some losses brought about by the emission of X-rays. The same problems apply, to a smaller degree perhaps, in regard to the requirement of a long mean-free path. This would limit the range of electron beams as a mode of energy transfer.

Of the above energy transfer modes, that mode which seems to have the best possibility of being applicable to long range operation through the atmosphere is electromagnetic radiation in the infrared region. Soft X-rays would probably rank very close if there was presently a method of producing X-rays in a power density approaching that needed to affect materials. We already have a device (the LASER) which will produce infrared radiation of the proper power density, but as of yet, only in short pulses. The prospect of using electron beams would be most attractive in regard to efficiency if some method were discovered to increase the effective mean-free path of the electrons through the atmosphere. There has been no indication of any solution of this problem to date.

John D. Myers
John D. Myers

cc: R. C. Abbott
G. F. Buranich (2)
J. W. Ford
R. E. Kell
D. P. Malone
J. D. Myers (4)
P. Rosenthal
File: C35-001
Serial
Extra (3)

GENERAL REFERENCES

1. Harnwell: _Prin. of Elect. and Mag._ (583)
2. Zemansky: _Heat and Thermodynamics_ (104)
3. Handbook of Chem. and Phys. 39 ed.
4. Hoag: _Electron and Nuclear Physics_
5. Estermann: Methods of Experimental Physics, Volume I, Classical Methods
6. Memo to Paul Rosenthal from J. D. Myers, August 2, 1961, File: C27-006, _Feasibility of Ion Beam Machining_