ION BOMBARDMENT AND ITS EFFECTS ON THE OPTICAL PROPERTIES OF METALS

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INTRODUCTION

Future interplanetary probes or space stations may require precise temperature control for several years or longer. For example, precision instrumentation or optical systems may require the ambient temperature to be within the range 15° to 25° C (60° to 78° F) for the length of the mission (ref. 1). Such requirements demand a knowledge of the effect of the spatial environment on the temperature control surfaces of a vehicle.

The thermal equilibrium of a surface in the spatial environment is primarily dependent upon a radiative energy balance between the surface and its environment. According to the laws of radiation energy transfer (ref. 2), this energy balance is related to the absorptance and emittance of the vehicle surface. The surface temperature of the vehicle varies as the fourth root of the α/ϵ ratio. It is, therefore, necessary to evaluate any change in this ratio caused by the spatial environment in order to properly design the thermal control of any vehicle.

The emittance and absorptance of a surface are strongly dependent on the finish of that surface and, thus, could be altered by the environment. One component of this environment of concern is high-energy particles. These particles can bombard a space vehicle and cause the ejection of surface atoms. This ejection is commonly called sputtering. According to reference 3,

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sputtering can change the optical properties of a metallic surface. However, as indicated in this reference, there is a lack of quantitative information in this field. This lack of information led to an experimental program to evaluate the change in total hemispherical emittance and solar absorptance of some engineering metals.

MATERIALS

Three materials were selected for test: titanium alloy containing 6-percent aluminum and 4-percent vanadium, 99.99-percent pure aluminum, and electrolytic copper. These materials were selected because they are considered to be representative of structural materials.

EQUIPMENT

The test equipment consisted of a sputtering apparatus, an integrating sphere reflectometer, and an emittance-measuring apparatus.

Sputtering Apparatus

The principle of cathode sputtering was used to bombard the metallic specimens with normally incident ions of hydrogen gas at an energy level of 1000 electron volts. A vacuum system with a 4-inch-diameter oil diffusion pump was used to evacuate a 5-inch bell jar to a background pressure of 1×10^{-6} torr. A hollow cylinder specimen was located in the center of the bell jar and was the negative electrode or target. A grid around the target provided a reference potential and also shielded the target from the ion sheath. The specimen mount had the necessary piping and seals to allow the circulation of cooling air at room temperature and pressure on the interior surface of the specimen.

Hydrogen gas was bled into the bell jar and was ionized by a single sideband, radio frequency transmitter. This transmitter was operated in a continuous wave mode and supplied power to a resonant circuit at 28 mcps. The ion accelerating potential was supplied by an external direct-current power supply set at 1000 volts. This type of sputtering apparatus is capable of producing an ion current of about 1 ma/cm^2. (A complete description of this apparatus is given in ref. 3).

Integrating Sphere Reflectometer

The reflectance of the specimens was measured in an integrating sphere reflectometer. Energy from a tungsten or hydrogen lamp was chopped at 13 cycles per second and directed into the entrance slit of a Perkin-Elmer Model 98 Monochrometer. The chopped monochromatic energy emerging from the monochrometer exit port was directed through the sphere entrance port. This energy was incident upon the specimen, and then reflected onto the sphere wall. This wall and all exposed parts of the specimen holder were coated with 2 mm of smoked magnesium oxide because of its high reflectance at the wave lengths of interest. Photomultiplier and lead sulfide detectors were located on the sphere wall to detect the intensity of wall illumination. This intensity was then used to determine the specimen reflectance.

Emittance-Measuring Apparatus

The emittance-measuring apparatus employed the calorimetric technique whereby the total hemispherical emittance of a body was determined from the steady-state radiative heat flow from that body to another completely enclosing body.

The entire cold-wall enclosure and specimen assembly were contained within a standard 18-inch bell jar. The chamber was evacuated by a vacuum system which utilized a 4-inch-diameter oil diffusion pump, a mechanical pump, and liquid-nitrogen-cooled baffles. The interior of the cold-wall enclosure was first sandblasted and then sprayed with three coats of black sicon paint. A liquid-nitrogen cooling coil was soldered to the outside of the enclosure.

The test specimen was heated with an internal electrical heater element. The current and voltage measurements required to evaluate the power input were made with the aid of a potentiometer and standard resistors.

The specimen was suspended within the cold wall by the specimen heater power leads. To minimize the heat conduction losses along these power leads, they were clamped in a guard heater at the point where they passed through the cold-wall enclosure. A more complete description of the emittance apparatus is given in reference 3.

TEST PROCEDURE

The procedures for sputtering the specimens and for determining their emittances and absorptances were essentially the same for all materials. The experimental program was run in two separate parts. First, the change in emittance was measured as a function of the amount of sputtering. The specimen was then repolished, the test was repeated, and the solar absorptance was measured.

The initial step, in each part, was to determine the emittance or absorptance for the polished surface. Photomicrographs were taken and the specimen was weighed. Then the specimen was subjected to several periods of sputtering. After each period, the specimen was again weighed, photomicrographs were made, and the total hemispherical emittance or solar absorptance was measured. This procedure was arbitrarily continued until about 10^{21} ions/cm^2 had bombarded each specimen.

Sputtering Procedure

After a specimen had been installed in the sputtering apparatus, the system was evacuated and purged with hydrogen for a period of 5 minutes. The hydrogen flow rate was then reduced to obtain the operating pressure of 0.01 torr. Sputtering was initiated by ionizing the gas with R-F excitation and by applying the negative 1000 volt potential to the specimen. The R-F field strength and the ion acceleration potential were maintained as constant as possible for all tests. To maintain the specimen temperature below 250° F, air was circulated through the interior of the model while it was being sputtered.

Reflectance-Measuring Procedure

Reflectance measurements were made at 50 points in the wave-length region of 0.3 to 3.0μ. Each point represented the reflectance for a 2-percent increment of the solar spectrum outside the earth's atmosphere. The desired wave length and slit width was set on the monochrometer to obtain each data point. With the optical beam incident on a selected reference area of the sphere wall, the recorder was adjusted to read 100 percent. The sphere was then moved to bring the specimen into the optical path. The resultant recorder reading represented the specimen reflectance at the set wave length. Since absorptance equals one minus reflectance at any specific wave length, the absorptance is then easily calculated. Integration of these values over the solar wave-length range produces the solar absorptance.

Emittance-Measuring Procedure

Total hemispherical emittance measurements were obtained in the following manner: First, the specimen and guard heater assembly was placed inside the cold wall and the system evacuated to approximately 1×10^{-5} torr. Next, power was applied to the specimen heater and when thermal equilibrium was obtained between the specimen (at 100° C) and the liquid-nitrogen cooled enclosure, the current and voltage were recorded. These measurements were used to calculate the power input to the specimen and, in turn, to determine the specimen emittance.

RESULTS AND DISCUSSION

The results of this experimental program are presented in figures 1 through 5.

It has been stated that sputtering can roughen a surface and thereby change the optical or radiative properties of that surface. This roughening is indicated in figure 1, which shows the surface finish of copper and aluminum specimens before and after sputtering. The before photomicrographs are for the electropolished surfaces in each case. The after pictures show the surfaces as they appeared after being bombarded by 10^{21} ions/cm^2. After sputtering, the texture of the copper is much different from that of the aluminum surface. The copper grains or crystals have been differentially attacked by sputtering, causing large variations in the height of each crystal. However, the surface of each crystal is relatively flat. For the aluminum surface, there is little, if any, difference in crystal height shown in the photomicrograph. The sputtering has, in this case, formed very small irregularities. The changes in the optical properites of the surfaces due to the formation of such irregularities will be shown in figures 2 through 5.

Absorptance Changes

Figure 2 shows the spectral absorptance of the aluminum specimen before and after sputtering. The wave length is from 0.3 to 3.0 microns, which covers the solar spectrum of interest. Sputtering did not basically alter the shape of the curve but did approximately double the absorptance at each wave length. Integration of such spectral absorptance curves over the solar spectrum produces the solar absorptance for each material tested. The effect of ion bombardment time on solar absorptance was then determined for the three materials tested.

The absorptance of these materials is presented in figure 3. The top curve represents the solar absorptance of titanium alloy as a function of number of bombarding ions. There is an initial change in absorptance, then almost a constant value thereafter. The maximum increase in absorptance was approximately 15 percent.

The middle curve shows the data obtained on the pure copper specimen. The change in absorptance of this material was very similar to that of the titanium alloy. The maximum increase in absorptance was also 15 percent. It should be noted that, in both cases, this maximum resulted from small amounts of sputtering.

The lower curve shows the increase in absorptance for the pure aluminum specimen. After the initial sputtering period, there is an almost linear increase in absorptance with increasing numbers of bombarding ions. The value of absorptance more than doubled, from approximately 0.10 to about 0.23, during the experiment. An interesting fact is that approximately 25 times as much material by weight was sputtered from the copper specimen than from the aluminum specimen. From this it can be seen that the amount of material removed from a surface is not a valid criterion by which to estimate the change in absorptance of that material.

Emittance Changes

The total hemispherical emittance of titanium, aluminum, and copper as a function of number of bombarding ions is presented in figure 4. The top curve shows the emittance of the titanium alloy specimen. It can be seen that bombardment by 10^{21} ions/cm^2 caused essentially no change in emittance of this material.

The middle curve shows the change in emittance for pure aluminum. The emittance increased to a value about 60 percent greater than the emittance of the polished surface and then remained essentially constant with increased sputtering. The lower curve shows the emittance of the pure copper specimen as a function of number of bombarding ions. The data indicate that the emittance increased by about 35 percent as a result of sputtering. After the first sputtering period, the emittance remained essentially constant throughout the rest of the test.

Changes in α/ϵ Ratio

From the data of figures 3 and 4, the effect of sputtering on the α/ϵ ratio of these materials can be shown. Figure 5 presents these results. As indicated, the ratio may increase or decrease, depending upon the material. The greatest change was exhibited by the aluminum specimen which went from an α/ϵ of 3.20 to 5.25, or a 65 percent increase. It should be noted that for the other materials, the maximum rate of change occurred during the initial part of the test.

Bombardment Rates in the Space Environment

The length of time for a surface to be bombarded by a specific number of ions depends upon the ion flux density of its environment. Current estimates from reference 4 indicate that the proton flux in the spatial environment during a quiet sun period is about 10^9 protons/cm^2/sec. During solar maxima, the flux may increase by three orders of magnitude.

If a surface is subjected to the spatial environment during solar maxima (10^{12} protons/cm^2/sec), the full scale of the abscissa (1×10^{21} ions/cm^2) in figures 3, 4, and 5 corresponds to a time of about 30 years. If it is assumed that the integrated effect of the solar wind (protons plus other heavier ions) is equivalent to that of the hydrogen plasma in this experiment, it appears that, for all materials tested, times of about a year could cause the significant initial emittance and/or absorptance changes shown in figures 3 through 5. For other than solar maxima conditions, this time would be correspondingly longer.

If, on the other hand, the environment has the much higher flux which might be encountered in an ion propulsion system, the time required to bombard a surface with 10^{21} ions/cm^2 could be reduced to hours. Thus, each material must be evaluated in its particular environment to determine whether the emittance and/or absorptance and, hence, the thermal energy balance of that surface will be significantly altered.

Temperature Control

The previous data have shown how the α/ϵ ratio changes as a result of ion bombardment. Figure 6 shows the relationship between the α/ϵ ratio and the equilibrium temperature of a spinning spherical satellite. For this calculation, it is assumed that there is no internal power, Q_i, generated within the vehicle so that the surface temperature is a function of the α/ϵ ratio and the distance of the vehicle from the sun, r, which for this case was 1 astronomical unit. This is a grossly simplified calculation; however, it demonstrates the magnitude of temperature variations which are possible. The dotted lines indicate the initial and final α/ϵ ratios of aluminum and the corresponding temperatures. The temperature increased from 372° K to 423° K. This is about a 50° K or 90° F increase. For the materials tested, the minimum corresponding temperature change was 11° K. These temperature variations could present a very serious problem in the case of temperature-sensitive components or experiments in a space vehicle.

CONCLUDING REMARKS

This investigation has shown that emittance, absorptance and α/ϵ ratio of the materials tested are, in general, changed by ion bombardment. The resultant temperature variations could, in some applications, be a serious problem. The time period in which significant changes would occur depends on the intensity of proton bombardment in the space environment, which is not accurately known and is subject to wide variations. Thus, the time may vary from less than a year to 30 years or longer, depending on the material and the environment assumed.

This experimental program is being continued to evaluate the effect of hydrogen ion bombardment on the α/ϵ ratio of thin films and optical coatings of greater interest as thermal control surface materials for space vehicles.

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FIGURE TITLES

Figure 1.- Photomicrographs of pure copper and pure aluminum specimens before and after sputtering.

Figure 2.- Effect of hydrogen ion bombardment on the spectral absorptance of pure aluminum.

Figure 3.- Effect of hydrogen ion bombardment on solar absorptance of metals.

Figure 4.- Effect of hydrogen ion bombardment on total hemispherical emittance of aluminum, titanium, and copper.

Figure 5.- Effect of hydrogen ion bombardment on the α/ϵ ratio of metals.

Figure 6.- Effect of α/ϵ ratio on the equilibrium temperature of a spherical satellite.

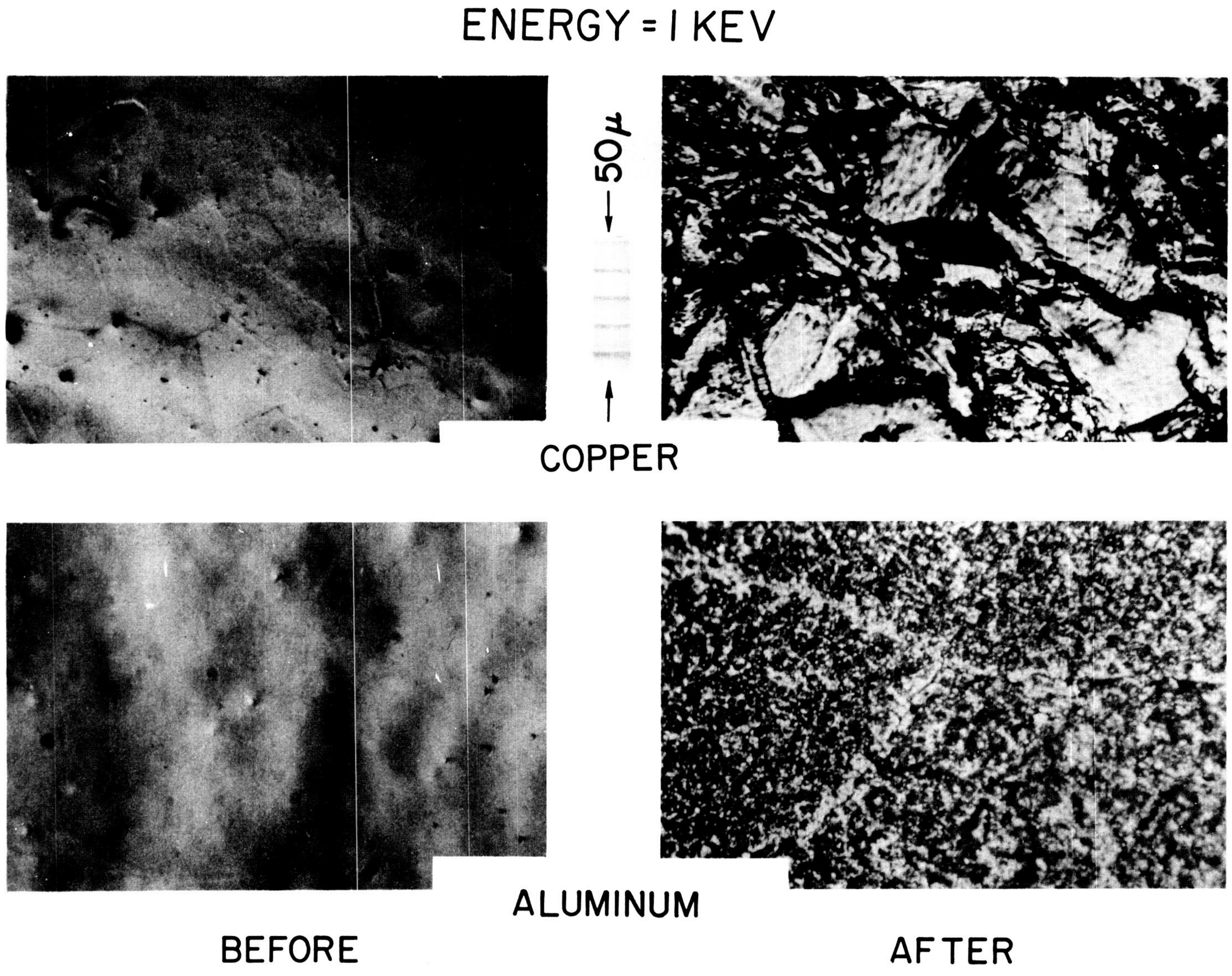

Figure 1. - Photomicrographs of pure copper and pure aluminum specimens before and after sputtering.

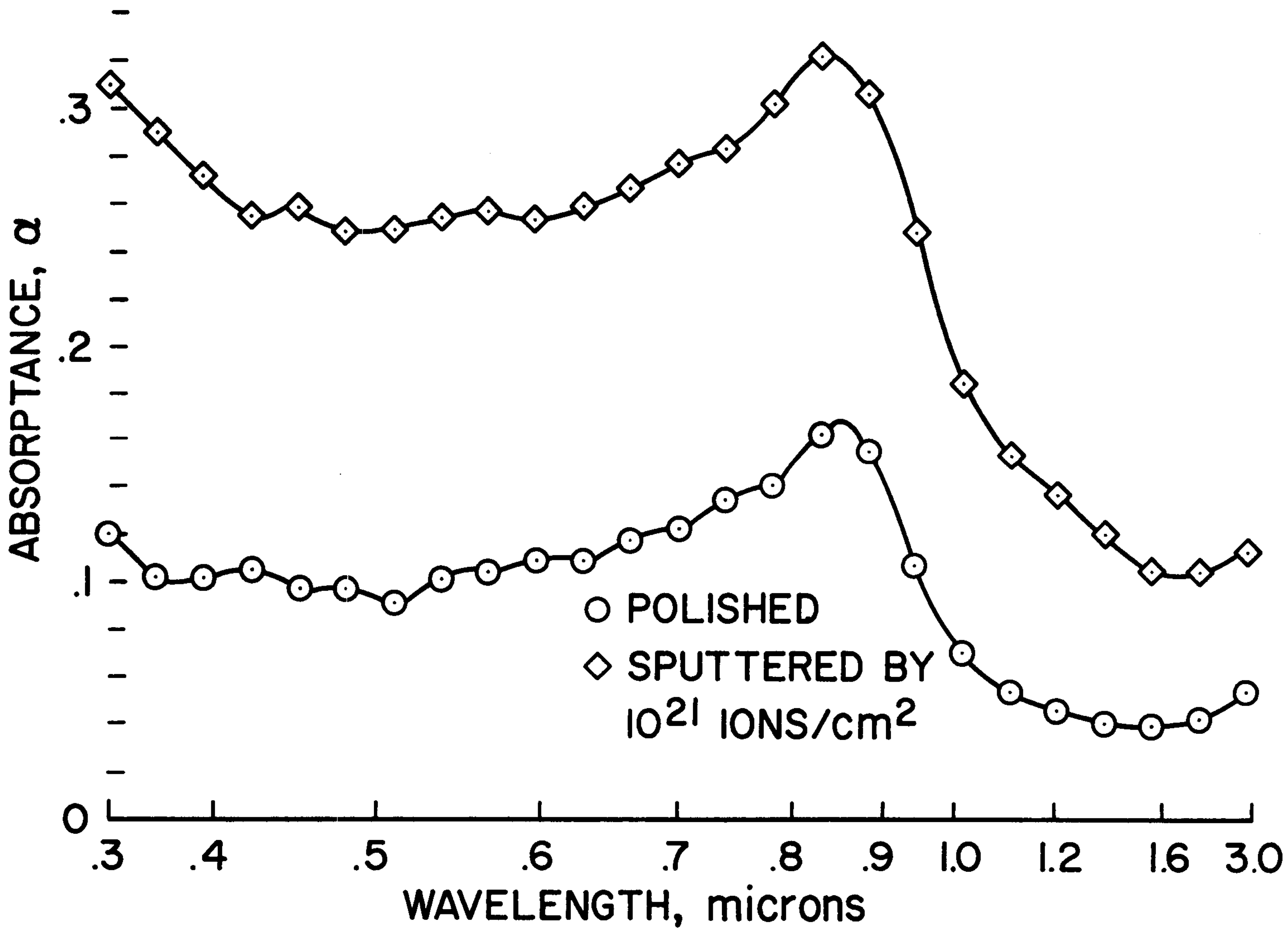

Figure 2. - Effect of hydrogen ion bombardment on the spectral absorptance of pure aluminum.

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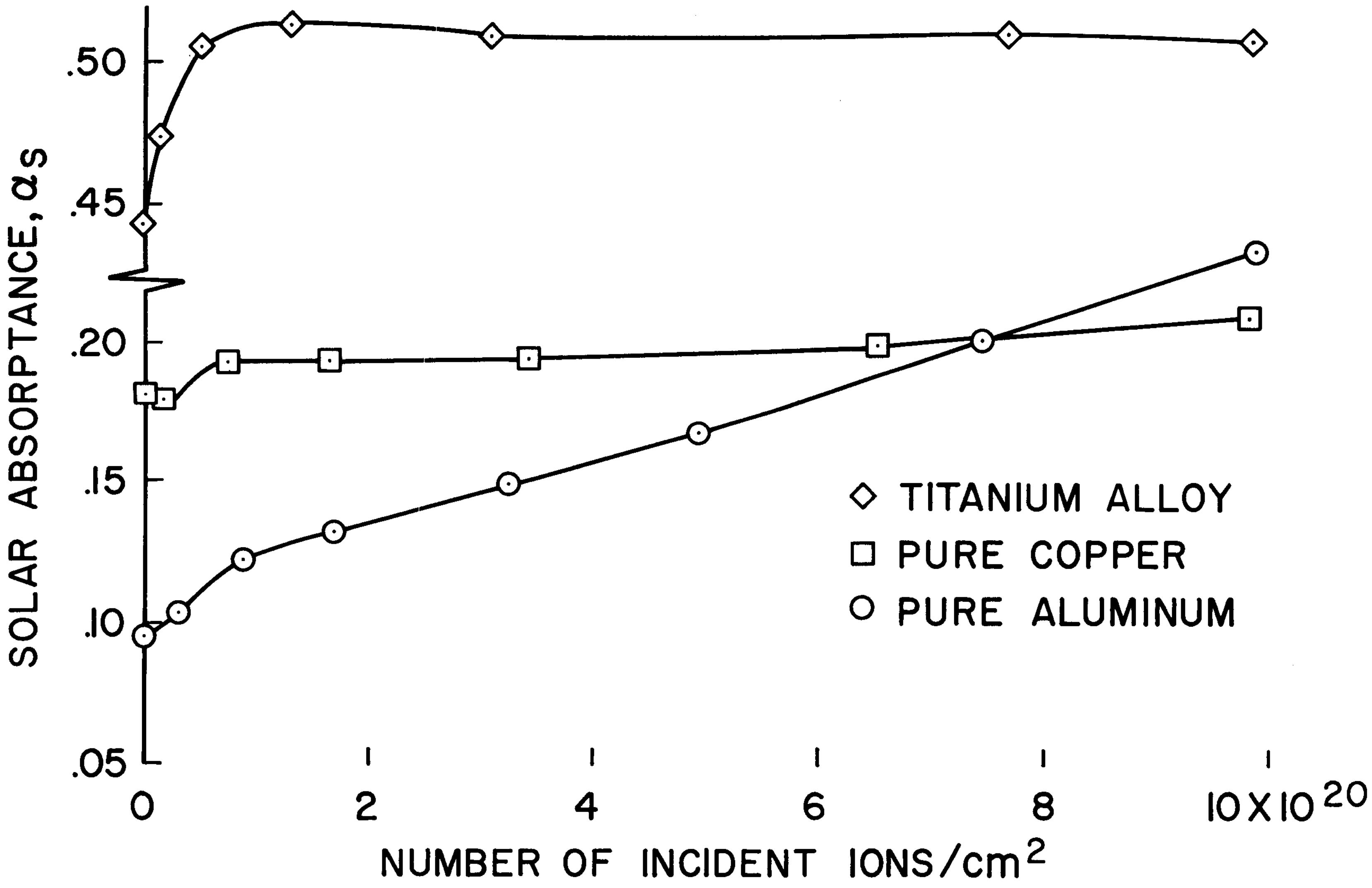

Figure 3. - Effect of hydrogen ion bombardment on solar absorptance of metals.

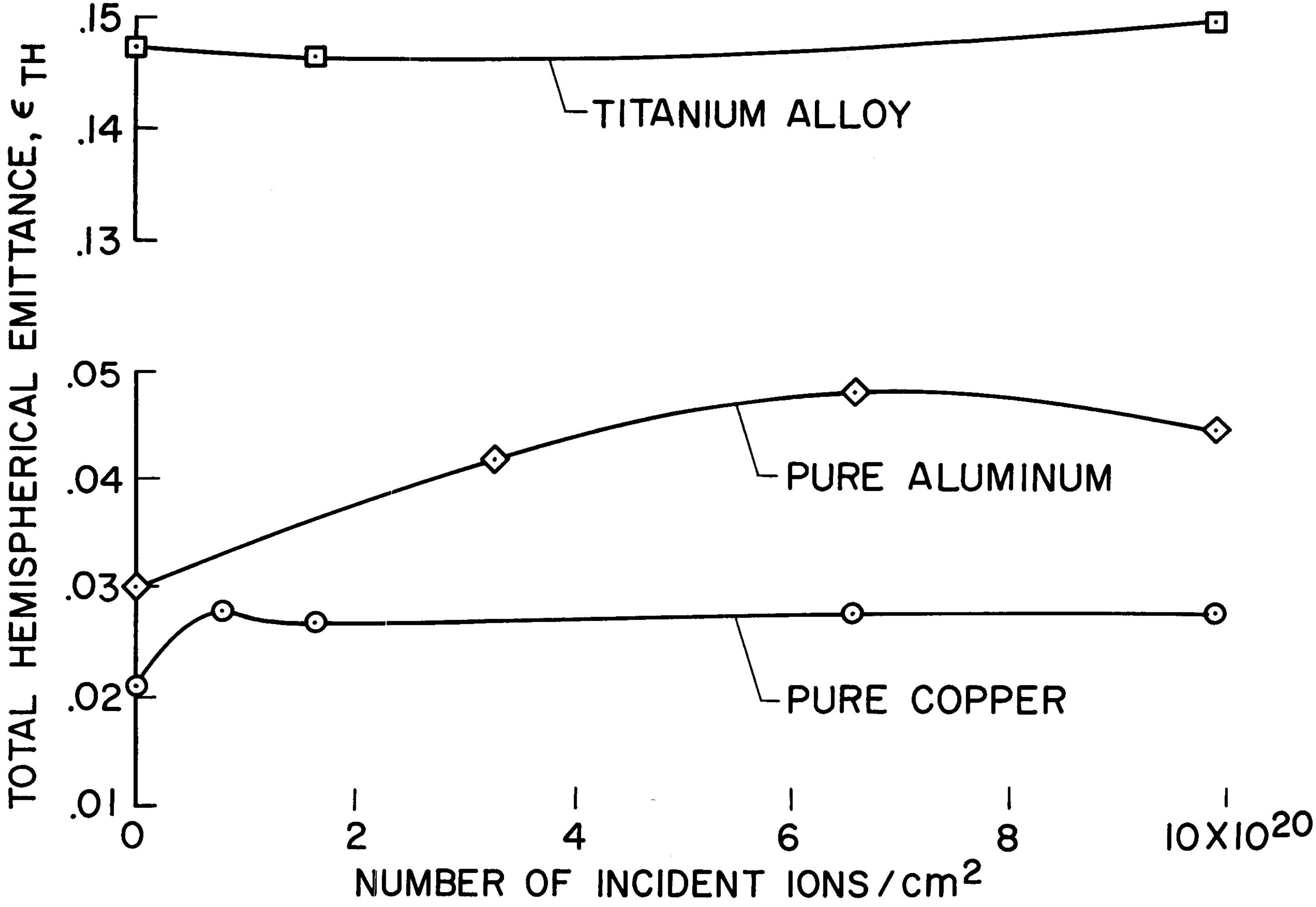

Figure 4. - Effect of hydrogen ion bombardment on total hemispherical emittance of aluminum, titanium, and copper.

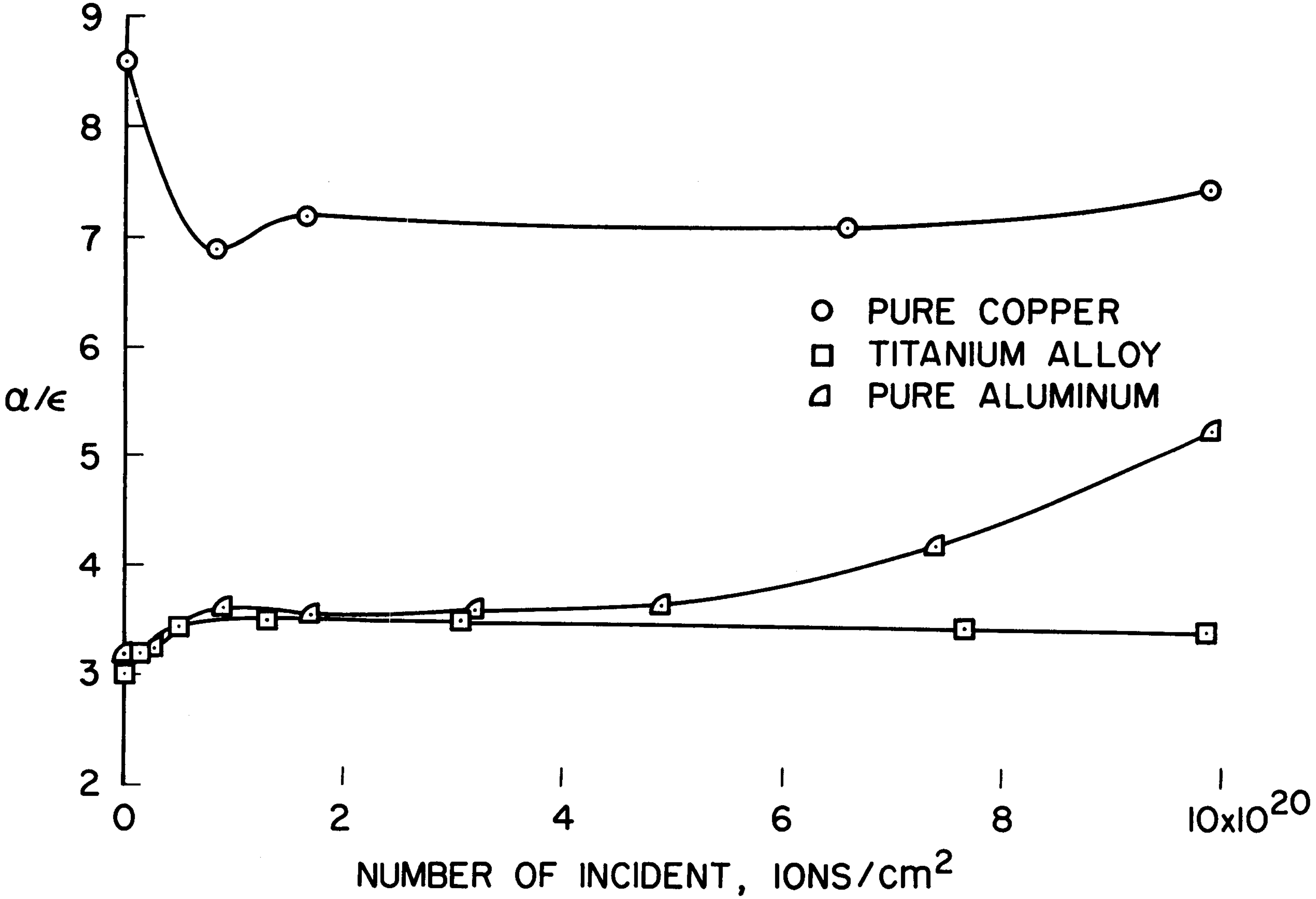

Figure 5. - Effect of hydrogen ion bombardment on the α/ϵ ratio of metals.

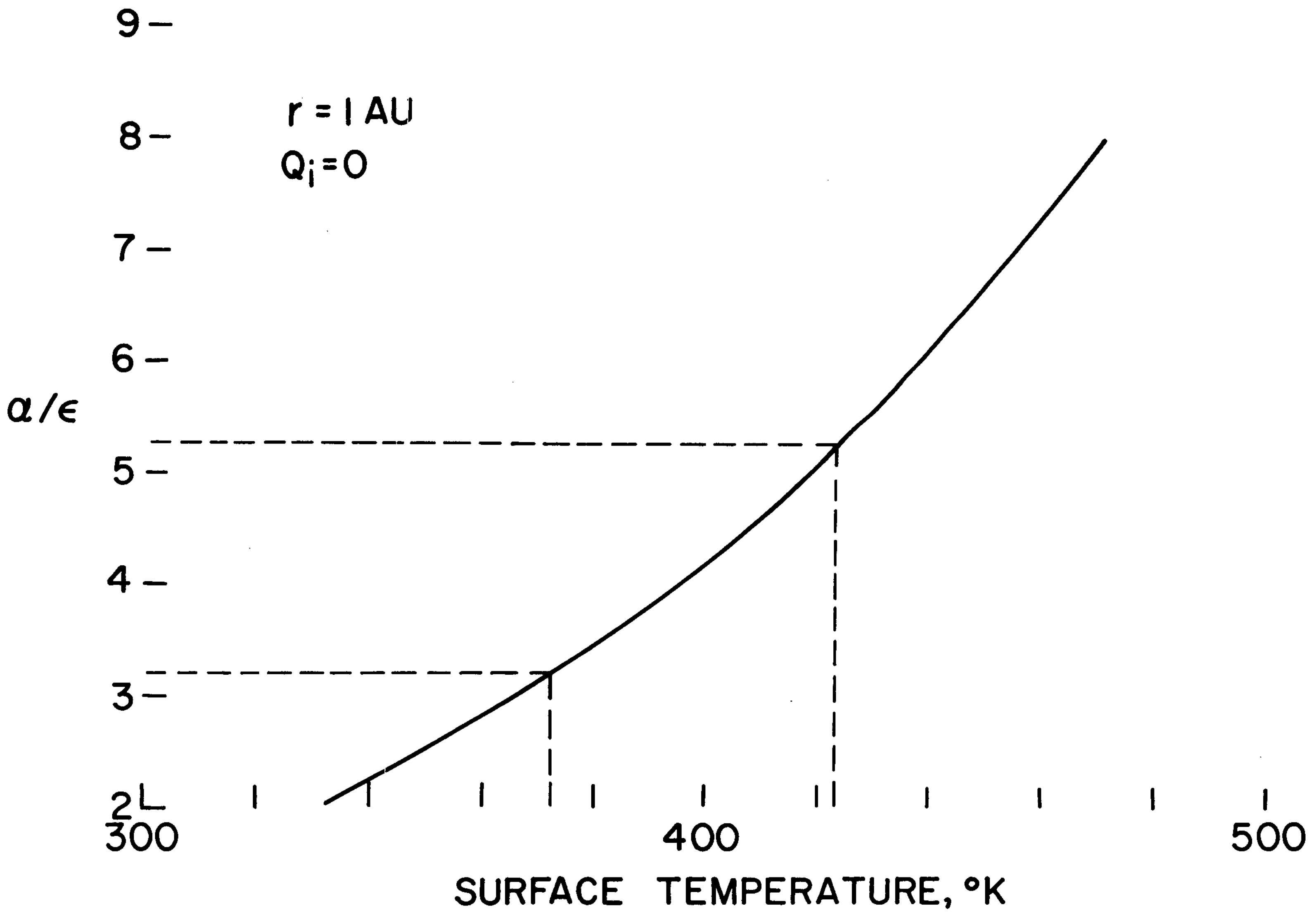

Figure 6. - Effect of α/ε ratio on the equilibrium temperature of a spherical satellite.