UHV - Hardware for Surface Studies

1. Types of Pumps used with UHV System to Study Surfaces:
   - Turbomolecular Pump (T)
   - Diffusion Pump (P)
   - Ion or Sputter Ion Pump (I)
   - Sublimation called Ti-Sublimation Pump (S)
   - Cryopumps (C)

2. Chambers, Tubes, Flanges sizes. Tubes and Flanges are STD (see catalogue)

Useful formula for Conductance as used for the handout, are the following:

Conductance Calculation Formula

(a) for an aperture axis diameter D (cm)

\[ C = 2.86 \left( \frac{T}{M} \right)^{1/2} D^{1/2} \text{ l/s} \]

M: molecular weight, 
T: Temperature (K)

(b) Conductance for long or short pipe with L (cm)

\[ C = 3.81 \left( \frac{T}{M} \right)^{1/2} D^{3} (L + 1.33D) \text{ l/s} \]
Flanges are made of St. Steel, and are sealed with Cu-gasket.

Choice of Materials

UHV expts. materials with low vapor pressure.

The main materials are St. Steel, Cu, Al, ceramic.

Bakeout temp. at ≤ 200°C.

Pressure Measurements for UHV System

(a) There are 3 general purpose gauges:

* Ion gauge < 10⁻¹³ mbar limit

* Pirani gauge < 10⁻³ mbar.

* Capacitance gauge < 10⁻⁴ mbar.

(b) Gas composition determined by mass spectrometer known as residual gas analyzer, like H₂, CO, H₂O dominated by outgassed system.
Instructional of UHV-Chamber Design

The important features of such system (UHV) used in surface physics are as follows:

1. The vacuum chamber and its associated pipelines are normally Argon-arc welded, or vac-brazed St. Steel.

2. Joints are made of metal instead of rubber O-rings.

3. The whole chamber assembly is designed so that it can be heated to above 200°C with vac. pumps operate.

4. The pumps provided to evacuate the chamber are often ion pumps, Ti sublimation, and for initial pumping from atmosphere pressure is sorption pumps.

5. Materials inside chamber, Mo, St. Steel, Ta, Cu, glass, Ceramic, Al203 as insulators to avoid high vapor pressure.

Fig: Shows Typical UHV System for Surface Studies.
Surface preparation

Having placed a sample for study in the UHV system and having achieved UHV environment for it, the next step is to attempt to obtain atomically clean surface upon which to conduct experiments.

Surface preparation procedure:

1. Evacuating UHV.
2. Heating sample near melting point for example Si (III) heated to 1870K for 1 min.
3. Heating in atmosphere for chemisorbed contamination removal.
4. By Bombardment with Ar⁺, Ne⁺ ions.
5. In situ prepare clean surface using Sb₁₁.
6. Evaporation on to a suitable substrate can be used in situ to prepare thin films.

Surface Cleansing

Methods of cleaning surfaces in High Vac Sys.

By Chemical Etching.

By Sputtering.

By Electron Beam desorption.

By Bulk heating or High Power Laser Pulse.

By Plasma Enhanced Chemical Vapor Deposition (PECVD).
Chapter 5.1

VAPORIZATION AND DRILLING BY LAZER

GENERAL INTRODUCTION

At the vicinity of the material, the laser beam is focused. The incident flux and the time of the pulse gives a change in temperature that will give boiling. Temp. For the material in time less than the pulse length.

When these conditions satisfied then vaporization established which has

\[
T(0,t) = \frac{2EF}{K_2} \left[ \frac{k_2t}{\lambda} \right]
\]

Where \( K_2 \) and \( k_2 \) are thermal constants of the substrate.

As its limiting speed, (Gonslaw 1959)

\[
v = \frac{EF}{(\lambda + pCt)}
\]

Where

- \( F \) : Incident intensity \((W/cm^2)\)
- \( \lambda \) : Heat of Vaporization \((J/cm^3)\)
- \( C \) : Specific heat \((J/g^\circ C)\)
- \( p \) : Emissivity at laser wavelength

\( F \) : assumed to be uniform at semi-infinite sheet, and all material is completely vaporized.

\* For good approximation

\[
v(t) = \frac{EF(t)}{(\lambda + pCt)}
\]
\[ \nu = \frac{x}{t} \]

\[ \int_{0}^{t} dx = \int_{0}^{t} \nu \cdot dt \]

\[ x(t) = \frac{1}{(\lambda + \rho C T) \cdot \omega} \]

where \( x(t) \): depth of penetration of the vaporization front at time \( t \).

So, the distance of the drilling depth can be equated.

1. If the drilling is to be done at low intensity, long idle isolated time are needed, and the fraction of available energy used for heating is very significant especially when drilling metals.

2. If short, high power pulse are to be needed then large fraction of the available energy can be used in the actual drilling process.

**Example:**

Cu - St. Steel drilling by high power Ruby Laser.

At low pulse energy, most of the incident energy is lost by conduction to the bulk material.

Copper has high thermal conductivity than St. Steel. So, less energy is available for vaporization and the drilling depth is smaller.
The energy needed for Cu vaporization ($\lambda + PCT$) is less than St. Steel.

So, greater drilling depth can be achieved in Cu.

**BULK HEATING AND VAPORIZATION**

If the heat equally dividing between the bulk heating and vaporization, if we equating the penetration distance of the heat ($x$) into the solid produced by half the flux, then, we have:

$$U t_p = \sqrt{kt_p} \quad (5)$$

Called Drilling depth = called characteristic heat penetration.

$$\sqrt{kt_p} = \frac{E (E^{\frac{1}{2}}) t_p}{(\lambda + PCT_{vap})} \quad (6)$$

and therefore:

$$F = \frac{2}{E} \left( \frac{k}{E} \right)^{\frac{1}{2}} \frac{\lambda + PCT_{vap}}{t_p} \quad (7)$$

where, $F$: incident intensity (watt/cm²)

If $t_p = 10^{-6}$ sec, $E$ is typically 0.1 for metals.

Then $F = 10^6 \text{ to } 10^7$ W/cm² for metals

$F = 10^5$ W/cm² for insulators at $E = 1.0$
If \( t_p = 10^{-2} \) sec,

\[
F_{\text{metal}} = 10^4 - 10^5 \text{ W/cm}^2
\]

\[
F_{\text{insul}} = 10^3 \text{ W/cm}^2
\]

It is therefore easy to obtain high drilling efficiencies with INSULATORS for both CW and Pulse lasers.

While, with metals conductive lasers are always significant if atypical laser is used and often when atypical pulsed laser is used.

\[ \text{DRILLING WITH LOW INTENSITY PULSES} \] \[ \text{At Power} \ 10^6 \text{ W/cm}^2 \]

\[ T = T_b \]

\[ T_b : \text{Boiling Temp.} \]

\[ P = \pi A R^2 T_b / \varepsilon(T_b) \]

See \( P \) watt \( A \) cm for CO\(_2\) Laser.

Minimum Values of \( P/A \) for the production of boiling on the surface with 10.6\( \mu \)m Focused laser circular area of radius \( A \) cm.

<table>
<thead>
<tr>
<th>Material</th>
<th>Al</th>
<th>Pb</th>
<th>Mg</th>
<th>Cu</th>
<th>Zn</th>
<th>Ta</th>
<th>Mo</th>
<th>W</th>
<th>Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P/A(\times 10^4 \text{ W/cm}) )</td>
<td>291.2</td>
<td>9.2</td>
<td>56</td>
<td>5.3</td>
<td>6.8</td>
<td>11</td>
<td>12</td>
<td>6.9</td>
<td></td>
</tr>
</tbody>
</table>
After the onset of boiling, the rate at which drilling proceeds is determined by the conservation of energy equation:

\[ \nu = \frac{\varepsilon F}{(\lambda + \rho \gamma T)} \]

where we set \( T = T_b \), \( \rho = \rho_r \), and \( \varepsilon = \varepsilon(T_b) \).

\[ \nu = \frac{\varepsilon (P - P_c)}{A \pi^2 (\lambda + \rho \gamma T_b)} \]

Where \( F = \frac{1}{A \pi^2} \) is the area of circular cross-section.

Using the above equation to predict \( \nu \) and knowing the pulse time \( t_{\text{pulse}} \), the depth can be predicted:

\[ x = \nu (t_p - t_{\text{vap}}) = \frac{\varepsilon (P - P_c) t_p}{t_{\text{vap}}} \]

(9)

(10)

(11)

(12)

\[ x = \int_{t_{\text{vap}}}^{t_p} \frac{\varepsilon (P - P_c)}{A \pi^2 (\lambda + \rho \gamma T_b)} dt \]

where \( P = P(t) \).

\{ DRILLING WITH HIGH-INTENSITY PULSES \}

Conductive losses, \( q_{\text{cond}} \), are significant:

\[ q_{\text{cond}} = \frac{F}{K} \frac{dT}{dt} \]

For short irradiation times, Eqn below

\[ T(0,0,t) = \frac{2PE \sqrt{kt}}{A^2 \pi K} \left[ N_1 - i \cdot \text{erfc} \left( \frac{A}{2\sqrt{kt}} \right) \right] \]

(13)
For short irradiation times, the above equation reduced to

$$ T = \left( \frac{2 \pi e}{\pi A^2 K} \right) \left( \frac{1}{kt} \right)^{\frac{1}{2}} $$

One can predict $t_{\text{vap}}$ to onset of vaporization $T_b$

$$ t_{\text{vap}} = \frac{T^3 A^4 K T_b}{4 p^2 \varepsilon^2 \kappa} $$

$$ t_{\text{vap}} \propto \frac{1}{(\text{Intensity})^2} \text{ (milliseconds)} $$

For KW - CW lasers and much less for Normal Pulsed Laser, but varies greatly from one metal to another.

### Table

<table>
<thead>
<tr>
<th>Metal</th>
<th>Cu</th>
<th>Al</th>
<th>Ni</th>
<th>Mo</th>
<th>Zn</th>
<th>Ta</th>
<th>Pb</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F=10^6$ W/cm², $t_{\text{vap}}$ (μsec)</td>
<td>3.1</td>
<td>0.94</td>
<td>0.21</td>
<td>0.53</td>
<td>0.069</td>
<td>0.068</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>$F=10^8$ W/cm², $t_{\text{vap}}$ (μsec)</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Time to $t_{\text{vap}}$ to onset of vaporization of metal surfaces of Incident Intensities $F$ of 10.6 μm Radiation.
After the surface has reached the vapor temperature, removal of materials is governed by the conservation of energy equation:

\[ \nu = \frac{\mathcal{E} P}{\lambda + \rho C T} \]

and the thermodynamic eqn:

\[ \nu = C \exp \left( -\frac{\lambda Z}{\rho N K T_{\text{vap}}} \right) \]

\( C \): velocity of sound in the material
\( \lambda \): heat of vapor (energy per unit volume)
\( Z \): Atomic number
\( \rho \): Density
\( N \): Avogadro's number
\( k \): Boltzmann's constant.

\[ \frac{P}{\pi A^2} = \left( \frac{\mathcal{E}}{Z} \right) \left( \lambda + \rho C T_{\text{vap}} \right) \exp \left( \frac{\lambda Z}{\rho N K T} \right) \]

SEE FIGURES

Fig \[ \Rightarrow \frac{P}{\pi A^2} \text{ constant at low } T \]

T calc. are close to T boiling

\( T = T_b \) at low intensity pulse is justified.
At high intensity (Q-switched) the Temp. changes rapidly with intensity.

Now using:

\[ V = \frac{\varepsilon P}{\pi A^2 (\lambda + P c T_{\text{trap}})} \]

and \[ V = C \exp\left(\frac{-\lambda Z}{\varepsilon N k T_{\text{trap}}}\right) \]

to predict \( V \) and knowing the duration of the applied pulse \( t_p \), the depth of drilling \( X \) can be predicted from the expression:

\[ X = V (t_p - t_{\text{trap}}) \]

where \( t_{\text{trap}} \) is obtained from:

\[ t_{\text{trap}} = \frac{\pi^3 \varepsilon A^4 K^2 T_b}{4 P^2 \varepsilon^2 k} \]

This equation is the basis for the calculation of the depth of drilling. It is derived from the interaction between laser intensity and material properties.
LASER HEATING OF SOLIDS: Theory

INTRODUCTION

Laser Power (Watt)

Time Period

Side Effect

Laser System Specification

[Classical Heat Transfer theory]
SOLUTION OF BASIC HEAT EQUATION

HEAT EQUATIONS

$$\nabla^2 T - \frac{1}{k} \frac{\partial T}{\partial t} = \frac{A(x, y, z, t)}{k} \quad (1)$$

The conduction of heat (solid yew) in 3D solid is given in general by the solution to the equation

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{\partial x^2} (k \frac{\partial T}{\partial x}) + \frac{1}{\partial y^2} (k \frac{\partial T}{\partial y}) + \frac{1}{\partial z^2} (k \frac{\partial T}{\partial z}) + A(x, y, z, t) \quad (2)$$

Where:
- \( K \) : Thermal conductivity
- \( \rho \) : Density
- \( c \) : Specific heat
- \( K, \rho, c \) : are dependence on \([T]\) and position \(x, y, z\).

\( A(x, y, z, t) \) : Heat supplied to the solid at the rate \([A]\) per unit time per unit volume.

Thermal diffusivity \( \frac{K}{\rho c} \)

Thermal properties of most materials do not vary greatly with \([T]\).

They can often be assumed independent of \([T]\) for practical purposes and can be assigned an average value of the \(T\)-range of interest.
Assume the solid is taken to be homogeneous and isotropic (steady state case), then eqn 2 then reduced to:

\[ \nabla^2 T + \frac{1}{k} \frac{dT}{dt} = \frac{A(x, y, z, t)}{K} \tag{1} \]

Where \( k = \frac{K}{PC} \)

In steady state, \( \frac{dT}{dt} = 0 \) \( \tag{3} \)

Substitution 3 in 1

\[ \nabla^2 T = \frac{A(x, y, z, t)}{K} \tag{4} \]

Eqn 1 and 4 can be solved in a large number of cases.

If no heat is supplied to the material, then

\[ A = 0 \] and Eqn 1 becomes

\[ \nabla^2 T = \frac{1}{k} \frac{dT}{dt} \tag{5} \]

[This is called Time Dependence Case]

Also when \( A = 0 \), Eqn 4 becomes

\[ \nabla^2 T = 0 \tag{6} \]

[This is called Steady State Case]
In practice, \textit{Cases} in which heat sources are present or absent are solved by imposing (steps) on the solutions of (5) and (6), the \textit{appropriate boundary conditions} of applied heat flux and heat transfer across the surface of the solid.

\textbf{BASIC DATA:} \textit{بيانات أساسية}

\textbf{Thermal Constants:} \textit{كانت الاستمالات الحرارية}

\begin{itemize}
  \item 1. \textbf{\textit{K}} \hspace{1cm} \left[\text{W/cm\cdot{}C}\right]
  \item 2. \textbf{\textit{k}} \hspace{1cm} \left[\text{Cm/Sec}\right]
  \item 3. \textbf{\textit{Cp} or \textit{C}} \hspace{1cm} \left[\text{J/gm\cdot{}C}\right]
  \item 4. \textbf{\textit{ρC}} \hspace{1cm} \left[\text{J/\text{cm}^3\cdot{}\text{C}}\right]
\end{itemize}

\textbf{اكاديات الاضلاع والاضلاع المتصلية:}

1. \textit{Thermal Conductivity Data}
2. \textit{Sp. Heats}
3. \textit{Thermal Diffusivity}
Thermal Conductivity Data for Some Metallic and Nonmetallic Solids

<table>
<thead>
<tr>
<th>Material</th>
<th>273°K</th>
<th>500°K</th>
<th>1000°K</th>
<th>2000°K</th>
<th>3000°K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2.36</td>
<td>2.38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromium</td>
<td>0.948</td>
<td>0.85</td>
<td>0.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>1.04</td>
<td>0.745</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>4.01</td>
<td>3.85</td>
<td>3.56</td>
<td>1.82</td>
<td>1.88</td>
</tr>
<tr>
<td>Gold</td>
<td>3.18</td>
<td>3.09</td>
<td>2.78</td>
<td>1.29</td>
<td>1.25</td>
</tr>
<tr>
<td>Iron</td>
<td>0.835</td>
<td>0.615</td>
<td>0.325</td>
<td>0.425</td>
<td>0.465</td>
</tr>
<tr>
<td>Lead</td>
<td>0.255</td>
<td>0.325</td>
<td>0.215</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1.39</td>
<td>1.30</td>
<td>1.12</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>0.94</td>
<td>0.72</td>
<td>0.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platinum</td>
<td>0.715</td>
<td>0.72</td>
<td>0.785</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhodium</td>
<td>1.51</td>
<td>1.40</td>
<td>1.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>4.28</td>
<td>4.12</td>
<td>3.74</td>
<td>1.97</td>
<td>1.91</td>
</tr>
<tr>
<td>Tantalum</td>
<td>0.574</td>
<td>0.582</td>
<td>0.602</td>
<td>0.64</td>
<td>0.665</td>
</tr>
<tr>
<td>Tin</td>
<td>0.662</td>
<td>0.685</td>
<td>0.405</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>0.224</td>
<td>0.197</td>
<td>0.207</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>1.82</td>
<td>1.49</td>
<td>1.20</td>
<td>1.0</td>
<td>0.91</td>
</tr>
<tr>
<td>Uranium</td>
<td>0.270</td>
<td>0.317</td>
<td>0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.313</td>
<td>0.33</td>
<td>0.385</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>1.22</td>
<td>1.11</td>
<td>0.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconium</td>
<td>0.232</td>
<td>0.21</td>
<td>0.236</td>
<td>0.313</td>
<td></td>
</tr>
<tr>
<td>Armcoiron</td>
<td>0.747</td>
<td>0.593</td>
<td>0.323</td>
<td>0.635</td>
<td></td>
</tr>
<tr>
<td>302 Stainless steel</td>
<td>0.13</td>
<td>0.155</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>303 Stainless steel</td>
<td>0.15</td>
<td>0.16</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>304 Stainless steel</td>
<td>0.168</td>
<td>0.186</td>
<td>0.255</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alumel (94.9% Ni, 2% Mn, 2% Al, 1% Si)</td>
<td>2.9</td>
<td>3.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow brass (72% Cu, 22% Zn, 4% Pb, 2% Sn)</td>
<td>1.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inconel</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monel</td>
<td>0.213</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zircalooy 2</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beryllium oxide</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel oxide</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thoria (ThO₂)</td>
<td>0.15</td>
<td>0.06</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconia (ZrO₂)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al₂O₃ (polycrystalline)</td>
<td>0.397</td>
<td>0.20</td>
<td>0.078</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Pyrolytic graphite</td>
<td>22.3</td>
<td>11.3</td>
<td>5.3</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>MgO (polycrystalline)</td>
<td>0.106</td>
<td>0.054</td>
<td>0.025</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Fused quartz</td>
<td>0.0133</td>
<td>0.0162</td>
<td>0.0287</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO₂ (polycrystalline)</td>
<td>0.089</td>
<td>0.0588</td>
<td>0.0346</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td>0.002</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dolomite</td>
<td></td>
<td></td>
<td></td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Earth (0.15 gm/cm³)</td>
<td>0.0010</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td>0.015</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>293°K</td>
<td>300°K</td>
<td>300°C</td>
<td>300°K</td>
<td>300°C</td>
</tr>
<tr>
<td>--------------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.88</td>
<td>1.0</td>
<td>0.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromium</td>
<td>0.5</td>
<td>0.49</td>
<td>0.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>0.38</td>
<td>0.417</td>
<td>0.471</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>0.135</td>
<td>0.135</td>
<td>0.151</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>0.42</td>
<td>0.54</td>
<td>0.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>0.129</td>
<td>0.136</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.245</td>
<td>0.261</td>
<td>0.288</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>0.44</td>
<td>0.52</td>
<td>0.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platinum</td>
<td>0.132</td>
<td>0.188</td>
<td>0.152</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>0.231</td>
<td>0.258</td>
<td>0.275</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tantalum</td>
<td>0.137</td>
<td>0.164</td>
<td>0.154</td>
<td>0.174</td>
<td>0.237</td>
</tr>
<tr>
<td>Tin</td>
<td>0.226</td>
<td>0.254</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>0.52</td>
<td>0.58</td>
<td>0.74</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.132</td>
<td>0.158</td>
<td>0.15</td>
<td>0.175</td>
<td>0.203</td>
</tr>
<tr>
<td>Uranium</td>
<td>0.116</td>
<td>0.143</td>
<td>0.178</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.47</td>
<td>0.51</td>
<td>0.62</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>0.378</td>
<td>0.422</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconium</td>
<td>0.28</td>
<td>0.322</td>
<td>0.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brass</td>
<td>0.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Emissivity

E = \lambda (T)

Reflectivity: \( R(\lambda) \)

Transmittivity: \( T(\lambda) \)

Emissivity: \( C \)

Incident Radiation

Reflected Radiation

Transmittance

Reflectance

Reflected Radiation
For opaque materials an measurement of the reflectivity $R_\lambda(T)$ will suffice, since the emissivity $E_\lambda(T)$ or the fraction of the incident intensity absorbed is given by:

$$E_\lambda(T) = 1 - R_\lambda(T)$$

$\lambda$: Wavelength of incident radiation.
$T$: Target temperature.

In this section, the results of this calculation will be given and $E_{\lambda \mu m}(T)$ for some common metals will be tabulated. It must be stressed however, that this calculation and the numerical values for $E_{\lambda \mu m}(T)$ actually arrived at will be valid only for metals heated in vacuum without a surface oxide layer.
The presence of surface film will greatly increase emissivity $E_{10\mu m}(T)$.

The complex refractive index of a metal:

\[ m = n - \text{i}n' \quad (2) \]

This is common behavior, taking the form of an increase in both $n$ and $n'$ and a tendency for $n \geq n'$. The square of $m$ can be written:

\[ m^2 = \beta - \text{i}\gamma \quad (3) \]

As $m^2$ approaches to $(-\text{i}\gamma)$ as $\gamma >> 1$.

Since, from theory:

\[ \gamma = \frac{60 \lambda}{\rho} \quad (4) \]

Where $\lambda$: measured in (m)

$\rho$: resistivity measured in (Ω·m)

The limiting value of $m^2$ is:

\[ m^2 = -\text{i}\gamma \quad \text{at long } \lambda \]
Then: \[ m = \left( \frac{1}{2} \frac{m}{y} \right)^{1/2} (1 - i), \quad y \gg 1 \] (5)

For perpendicular incident radiation:

\[ E_\lambda(T) = 1 - R_\lambda(T) = 1 - \left[ \frac{m^{-1}}{m+1} \right]^2 \] (6)

The emissivity at long \( \lambda \) becomes:

\[ E_\lambda(T) \approx \left( \frac{8}{\eta} \right)^{1/2} \] (7)

where \( \eta \) is a function of \( \lambda \) and \( T \).

The absorption coefficient of the metal is given by:

\[ \kappa = \frac{4 \pi n^2}{\lambda} \left( \frac{1}{4} \frac{1}{\eta} \right)^{1/2} \] (8)

Following Bramson (1968), Eqn 7 may be expanded to give:

\[
\left[ E_\lambda(T) = 0.365 \left( \frac{P}{\lambda} \right)^{1/2} - 0.0667 \left( \frac{P}{\lambda} \right) + 0.006 \left( \frac{P}{\lambda} \right)^{3/2} \right] \] (9)
Where $\rho$ in $\Omega$ cm$^{-2}$ and $\lambda$ in cm.

The resistivity $\rho$ written as:

$$\rho = \rho_{20} \cdot (1 + d \Delta T)$$

$$\rho = \rho_{20} \cdot [1 + d(T - 293)]$$ \hspace{1cm} (11)

where $d$ : coefficient of resistivity.

For CO$_2$ laser at wavelength $\lambda = 10.6 \mu m$, this expression:

Now put (10) into (9), the result:

$$E_{\lambda}(T) = 0.365 \left[ \frac{\rho_{20} \cdot (1 + d \Delta T)}{\lambda} \right]^{\frac{1}{2}} - 0.0667$$

$$+ 0.006 \left[ \frac{\rho_{20} \cdot (1 + d \Delta T)}{\lambda} \right]^{\frac{3}{2}}$$ \hspace{1cm} (11)

For CO$_2$ laser, at $\lambda = 10.6 \mu m$, this expression (11) becomes:

$$E_{10.6 \mu m}(T) = 11.2 \left[ \frac{\rho_{20} \cdot (1 + d \Delta T)}{\lambda} \right]^{\frac{3}{2}} - 62.9 \left[ \frac{\rho_{20} \cdot (1 + d \Delta T)}{\lambda} \right]$$

$$+ 174 \left[ \frac{\rho_{20} \cdot (1 + d \Delta T)}{\lambda} \right]^{\frac{3}{2}}$$ \hspace{1cm} (12)
Barnson (1968) gives data on $E_{10.6 \mu m}$ that may be used to estimate $E_{10.6 \mu m}$ for most simple metals over a moderate range of $T$. Table 1 reproduces some of these data [$P_{20}$, $\lambda$] and Fig. 1 shows a generalized plot of $E_{10.6 \mu m}$ versus $(1 + aT)$ for $P_{20}$ in the range of $10^{-4}$ to $10^{-6}$ $\Omega$-cm.

We see that even metals with high resistivity, like Nichrome, $10^{-4}$ have a low value of $E_{10.6 \mu m}$ even at high $T$.

Thus, in the absence of surface oxidation or some processing that increases $E_{10.6 \mu m}$, most metals will absorb less than 20% of incident $\lambda = 10.6 \mu m$ radiation even at elevated temperatures.

The increase of $E_{10.6 \mu m}$ with $T$ means that progressively more incident radiation may be absorbed as $T$ increases.

Benett (1971) has published a detailed theoretical and experimental study of the reflectivities of several CO2 laser mirror materials.
<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho_{20}$ (Ω·cm)</th>
<th>$\alpha$ (Ω·cm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>$2.82 \times 10^{-6}$</td>
<td>$3.8 \times 10^{-1}$</td>
</tr>
<tr>
<td>Brass</td>
<td>$8.00 \times 10^{-4}$</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Bronze</td>
<td>$8.00 \times 10^{-4}$</td>
<td>$3.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Constantan</td>
<td>$4.90 \times 10^{-5}$</td>
<td>$1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>Copper</td>
<td>$1.72 \times 10^{-6}$</td>
<td>$4.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gold</td>
<td>$2.42 \times 10^{-6}$</td>
<td>$3.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>Invar</td>
<td>$7.8 \times 10^{-3}$</td>
<td>$2.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Iron</td>
<td>$9.80 \times 10^{-8}$</td>
<td>$5.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Manganese</td>
<td>$4.40 \times 10^{-5}$</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>$5.60 \times 10^{-5}$</td>
<td>$4.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>Nichrome</td>
<td>$1.00 \times 10^{-4}$</td>
<td>$4.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Nickel</td>
<td>$7.24 \times 10^{-5}$</td>
<td>$5.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Platinum</td>
<td>$1.05 \times 10^{-3}$</td>
<td>$5.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>Silver</td>
<td>$1.62 \times 10^{-3}$</td>
<td>$3.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>Steel alloy</td>
<td>$1.50 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>mild</td>
<td>$1.50 \times 10^{-5}$</td>
<td>$3.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>structural</td>
<td>$1.20 \times 10^{-2}$</td>
<td>$3.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Tantalum</td>
<td>$1.55 \times 10^{-3}$</td>
<td>$3.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>Tin</td>
<td>$1.14 \times 10^{-5}$</td>
<td>$4.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Tungsten</td>
<td>$5.50 \times 10^{-4}$</td>
<td>$5.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Zinc</td>
<td>$5.92 \times 10^{-4}$</td>
<td>$3.5 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

* From Bramson (1968).

---

**Fig. 6.1:** Emissivity at 10.6 μm for metals.