Table 2 . . . . Total Emissivities

| Surface | Temp—R | | | |
|---|---|---|---|---|
| | 7 | 37 | 140 | 540 |
| Copper | 0.0050 | | 0.008 | 0.018 |
| Gold | | | 0.01 | 0.02 |
| Silver | 0.0044 | | 0.008 | 0.02 |
| Aluminum | 0.011 | | 0.018 | 0.03 |
| Magnesium | | | | 0.07 |
| Chromium | | | 0.08 | 0.08 |
| Nickel | | | 0.022 | 0.04 |
| Rhodium | | | 0.078 | |
| Lead | 0.012 | | 0.036 | 0.05 |
| Tin | 0.012 | | 0.013 | 0.05 |
| Zinc | | | 0.026 | 0.05 |
| Brass | 0.018 | | | 0.035 |
| 18-8 Stainless steel | | | 0.048 | 0.08 |
| 50 Lead 50 Tin solder | | | 0.032 | |
| Silver plate on Copper | | 0.013 | 0.017 | |
| Nickel plate on Copper | | 0.027 | 0.033 | |

installing the couples so that heat will not flow along the wires and change the temperature of the junction. Thermocouples or multijunction thermopiles are very well suited for measuring small temperature differences, for example the temperature difference between the two streams of a heat exchanger. There is a special thermocouple material that has been used recently at very low temperatures. This is gold with an admixture of 2.11 atomic percent cobalt. A thermocouple using this material with copper as the other element has a much higher thermoelectric power than that of copper *vs* constantan. Sometimes the gold-cobalt alloy is paired with an alloy of silver with 0.37 atomic percent gold to avoid the good thermal conductivity of the copper. Table 1 gives the thermal emf of these materials. These are the emf of representative specimens

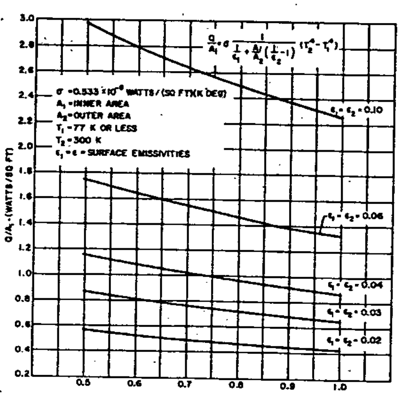



Fig. 8 . . . . Radiation Heat Transfer

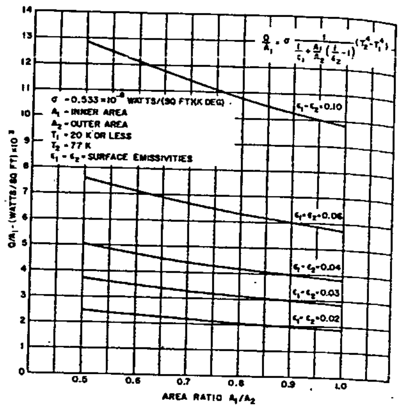



Fig. 9 . . . . Radiation Heat Transfer

of the thermocouple wires. Another thermocouple of the same nominal composition will deviate somewhat from these values but the differences should be so small that a few calibration points should be sufficient to establish a reliable deviation curve.

Resistance thermometers used at low temperatures employ one of two different types of temperature-sensitive materials, pure metals and semiconductors. The pure metal resistance thermometer has been in use for many years, being exemplified by the standard strainfree platinum resistance thermometer which is the interpolating instrument used to realize the International temperature scale from −183 to 630 C. Other pure metals, including copper, nickel, gold, lead and indium have been used. At room temperature the resistance of a pure metal wire is approximately proportional to the absolute temperature. At quite low temperatures the change of resistance decreases with temperature and finally becomes almost independent of temperature and accordingly useless as a thermometer material. The soft heavy elements such as lead and indium maintain a useful temperature coefficient of resistance to lower temperatures. The resistance coil should not be subjected to mechanical strain because this may cause the resistance to change. In the standard platinum thermometer strains are minimized by having the coil supported in notches in the edges of a mica cross. Some rather good thermometers have been made by winding the wire on a tube of the same material, for example copper wire on a copper tube.

Some semiconductors such as carbon or germanium with a very small amount of indium (e.g. 0.0005 atomic percent), have high temperature coefficients of resistance at very low temperatures. These are most useful below 20 K where the pure-metal resistance thermometer has decreased sensitivity. At temperatures below 4 K some germanium resistance thermometers were found to double their resistance when the temperature was lowered one degree. Semiconductors have negative temperature coefficients. For moderately low temperatures commercial thermistors, semiconductors made



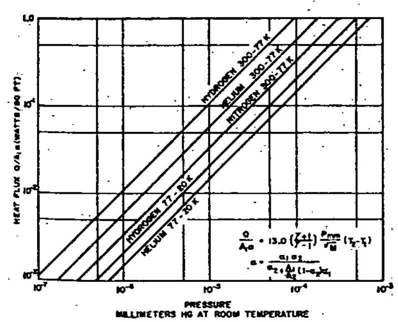
Table 3 . . . . Accommodation Coefficients

| Temp R | Helium | Hydrogen | Air |
|---|---|---|---|
| 540 | 0.3 | 0.3 | 0.8–0.9 |
| 140 | 0.4 | 0.5 | 1 |
| 37 | 0.6 | 1 | |
| 7 | 1 | | |

of metallic oxides, are useful. The principal advantage of semiconducting resistance thermometers is their high sensitivity. Their principal disadvantage is that there is no simple function that will express the temperature-resistance relationship. Also, few semiconductors have the stability of good metal resistance thermometers, although recent results with specially prepared germanium show excellent stability.

For very low temperatures the magnetic thermometer is used to establish the thermodynamic temperature. The magnetic thermometer consists of a specimen of paramagnetic salt such as chromium potassium alum and a means of determining its magnetic susceptibility. The susceptibility is approximately proportional to the reciprocal of the absolute temperature (Curie's relation), thus the sensitivity of the magnetic thermometer increases with decreasing temperature. There are deviations from the Curie relationship at very low temperatures but these can be corrected for and the true thermodynamic temperature determined if the susceptibility is first measured at a higher temperature where the thermodynamic temperature is known.

Liquid-in-glass thermometers filled with propane or a special mixture of pentanes can be used down to liquid oxygen temperatures or slightly below. The principal precaution in using such a thermometer is to make sure that the liquid has drained. This is best accomplished by immersing only the bulb at first, leaving the thermometer stem warm, then after a few minutes the immersion is completed.




$A_1$ is the inner area. $A_2$ is the outer area.
$a_1$ and $a_2$ are accommodation coefficients at the two boundaries.
$\gamma$ is the specific heat ratio of the gas.
$M$ is the molecular weight of the gas.
$T_1$ and $T_2$ are the boundary temperatures.
$P_{mm}$ is the gas pressure in mm Hg as indicated by a gage at room temperature.

Fig. 10 . . . . Gaseous Heat Conduction

Table 4 . . . . Structural Support Materials

| Material | Yield Stress psi | Thermal Conductivity[a] |
|---|---|---|
| Aluminum 2020 | 55,000 | 47 |
| Aluminum 7075 | 70,000 | 50 |
| Copper, annealed | 18,000 | 224 |
| Hastelloy[c] "B" | 65,000 | 5.4 |
| Hastelloy[c] "C" | 48,000 | 5.9 |
| "K" Monel[d] | 100,000 | 9.9 |
| Stainless Steel 304 (ann) | 35,000 | 5.9 |
| Stainless Steel (Drawn 210,000 psi) | 150,000 | 5.2 |
| Titanium pure | 85,000 | 21 |
| Titanium alloy (4Al–4Mn) | 145,000 | 3.5 |
| Dacron[e] | 20,000 | 0.088[b] |
| Mylar[e] | 10,000 | 0.088[b] |
| Nylon[e] | 20,000 | 0.18 |
| Teflon[e] | 2,000 | 0.14 |

[a] Average value between 20 and 300 K, Btu/(hr) (sq ft) (R deg/ft).
[b] Room Temperature value.
[c] Haynes Stellite Co.
[d] International Nickel Co.
[e] E. I. duPont de Nemours and Co.

## THERMAL INSULATION

### High Vacuum Reflective Insulation

In most well-designed Dewar vessels, heat transfer will occur predominantly by radiation and can be calculated by using well-known adaptations of the Stefan-Boltzmann formula, provided the emissivities of the surfaces enclosing the vacuum jacket are known. Table 2 gives minimum recorded values of emissivities of selected materials. Figs. 8 and 9 give radiation heat transfer for two sets of boundary temperatures that are of special importance in cryogenics. These data and the formula from which they were calculated apply for parallel plane, coaxial cylinder or concentric sphere configurations.

Good-reflecting surfaces are achieved in practice by such means as application of aluminum foil, chemical deposition of silver, or electro deposition of silver or gold. In Dewar vessels built of copper or aluminum, only a cleaning or polishing of the structural metal is required. Whatever the materials used to obtain low emissivities, it will be important to remove surface contaminants such as oxides or films of oil or grease. There will be some advantage in using cleaning procedures, such as solvent cleaning and electropolishing, that avoid work-hardening of the metal.

In Dewar vessels for the lowest boiling liquids, helium (7 R) and hydrogen (37 R), it is customary to intercept the radiation from the warm boundary by a shield cooled with liquid nitrogen (140 R). In such vessels a significant portion of the heat exchange between shield and inner container may be from conduction by residual gas in the evacuated space. In a hydrogen Dewar vessel the residual gas is likely to be hydrogen, released from solution or entrainment in the structural metals or resulting from decomposition of diffusion pump fluids. In a helium Dewar vessel such hydrogen is condensed on the helium-cooled surface, and residual gas can only result from leaks in the helium vessel.

Gaseous heat conduction at low pressures is calculated using adaptations of the Knudsen formula. In these formulas there appears the accommodation coefficient, a factor ex-