FIRE AND FLAMMABILITY HANDBOOK

NEIL SCHULTZ

FIRE AND FLAMMABILITY HANDBOOK

NEIL SCHULTZ

VNR VAN NOSTRAND REINHOLD COMPANY
New York

Library of Congress Catalog Card Number: 85-3275
ISBN: 0-442-28154-4

Manufactured in the United States of America

Published by Van Nostrand Reinhold Company Inc.
135 West 50th Street
New York, New York 10020

Van Nostrand Reinhold Company Limited
Molly Millars Lane
Wokingham, Berkshire RG11 2PY, England

Van Nostrand Reinhold
480 Latrobe Street
Melbourne, Victoria 3000, Australia

Macmillan of Canada
Division of Gage Publishing Limited
164 Commander Boulevard
Agincourt, Ontario M1S 3C7, Canada

15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

Library of Congress Cataloging in Publication Data

Schultz, Neil, 1952–
Fire and flammability handbook.

Bibliography: p.
Includes index.
1. Fire prevention. 2. Fire. 3. Flammability.
I. Title.
TH9145.S34 1985 628.9'22 85-3275
ISBN 0-442-28154-4

FOREWORD

Fire protection is one of the oldest technologies practiced by civilized societies—records exist from the days of the ancient Romans showing their efforts to develop fire protective treatments for timber. In today's society, fire protection occupies a peculiar role. Its need is acknowledged, and there are numerous legal requirements for fire protective features. (This technology is considered a branch of engineering.) Yet presently in the United States, there are less than 2000 fire protection engineers, and only about 50 are graduated each year. Fire protection engineering instruction is available at very few institutions (only one fully accredited program, plus two or three less comprehensive ones). Meanwhile, the demand for fire protection knowledge and skills is great—building code officials, architects, design engineers, fire marshalls, product development chemists, textile technologists, and naval architects are but a few of the many professionals who must have some basic skills in fire protection to be able to discharge their duties successfully. With the exception of firefighting textbooks, the training materials available are scant indeed. For many, the only way of learning has been to study the relevant portions of the NFPA (National Fire Protection Association) National Fire Codes. This material is very comprehensive for those areas where a rulebook approach is suitable. Nevertheless, it is clear that a textbook style of presentation can be much more approachable for the professional. In addition, some areas of fire protection, such as mathematical fire modeling, are so new that codes are not available. The professional can also develop a more fundamentally based knowledge if the "whys" and "wherefores" are given, as derived from basic principles.

Neil Schultz is the president of a fire testing laboratory where much of his activity has been addressed to developing new and improved fire testing procedures. To do this successfully, he has had to become knowledgeable in numerous aspects of heat transfer, structural design, chemistry, polymer science, textile technology, hydraulics, industrial hazard protection, and other areas of fire protection. From his experience, he has been able to compile an easy to follow textbook that provides the professional with both some fundamental underpinnings of the field, and practical guidance. The professional who reads and learns this material will not become an instant expert. He or she must still read the

NFPA National Fire Codes, and other standards documents that may be pertinent to a given task. After reading the *Fire And Flammability Handbook*, however, the professional will be able to easily and quickly find the required standards and employ them in his or her own work. The technical expositions, given in introductory form, may also whet the professional's appetite such that he or she will pursue more detailed studies of heat transfer, chemical reaction kinetics, building code development, etc., for which useful references are provided in the Bibliography. Furthermore, a number of important property tables are collected in the Appendix, and also at appropriate places in the body of the text—these will make the book of continuing value as a ready reference.

Vytenis Babrauskas
Gaithersburg, MD

PREFACE

During the course of over 100,000 years, nature ruled fire, while man remained a curious spectator—both benefiting and suffering from its effects. Man's first signs of control used fire as a tool to further advance society. Fire was used in manufacturing, providing energy, and running older modes of transportation. It was not until the Industrial Revolution of the 1800's that man tempered the ravages of a fully developed fire. During this time, however, fire was still man's enemy, destroying all in its path when uncontrolled.

The most prevalent method to stop a fire is to douse it with copious amounts of water. Man has provided a few other extinguishing agents, but water, by far, is the most popular.

In the last two decades, the academic world has started to investigate the nature of fire—that is, what actually occurs during the combustion process. Dr. Howard Emmons, the father of fire science, developed numerous concepts of combustion operation with the help of advanced technologies such as computers and lasers. Moreover, the federal government has become involved through the National Bureau of Standards, where continuous work is conducted on both practical and research levels.

My involvement began at a practical level in the early 1970's. I was working for a manufacturer of noise control products such as acoustic doors and walls. Many of the products were for the Veterans Administration, schools, and factories that required fire-resistant materials. As a research and development engineer, I was assigned to design, test, and achieve the necessary fire rating. It took about one full year to understand the fire technology required to produce the required fire-resistant products. After numerous fire tests at UL over a period of years, all product categories had fire rated designs.

The objective of this book is to reduce the amount of search time required to understand the fire technology field. Whether one is a chemist designing a flame-retardant foam, or a project engineer trying to understand a fire test, this text is the one, complete source from which any professional can get started, and use well into a project related to fire technology, at any level.

I would like to acknowledge Ms. Lora Goldstein for her assistance, and Drs. Martin Hoffert, Gabriel Miller, and Barry Rugg for providing me with the necessary theoretical tools to understand the science needed for fire technology.

NEIL SCHULTZ

CONTENTS

1. INTRODUCTION

FUNDAMENTALS

Heat transfer in fires has been widely studied in different countries. The understanding of fire does not lend itself to one discipline. It requires basic knowledge of fluid mechanics, transport phenomena, and chemical kinetics to comprehend mechanisms that relate to fire technology. True fire technologists are fire marshalls, as well as Ph.D.'s at universities. The position one has in the field does not always bear directly on his or her contributions.

The mathematics of heat transfer are easily handled on a pocket calculator and when possible, calculus is reduced to applied equations. Many equations are listed, but on close examination one will find they are rudimentary. It can be beneficial for the reader to review the basics before attempting to absorb other sections of this book. Some might require a quick review of basic mathematics, which can often be found in high school or college math textbooks and calculator instruction manuals.

Confusion sometimes arises because of the interchangeability of terms in the various fields of science and engineering. Mass is a measurement of the amount of matter, and is referenced in a standard established by Congress and carefully preserved at the United States Bureau of Standards. Force is a value, and pound force is the quantity of force, necessary to support the standard pound body against gravity in a standard locality. Mass and weight have the same numerical value when expressed in pounds, provided the object being weighed is balanced against standard weight.

HEAT TRANSFER

The result of all fire or combustion processes is the release of large quantities of heat. Often it is the heat release that causes other materials to explode, combust, or pyrolize, thereby releasing additional heat and/or products, which are toxic to humans. Understanding the different modes of heat transfer is essential to a complete understanding of fires, where a heat mode is the transfer of energy from one body to another, due to differences in body temperatures.

Table 1-1. Heat-transfer Nomenclature.
(Greek letters are grouped together following the English)

Symbol	Quantity	Units
a	Absorptivity	
a	Modulus $\frac{g\beta\rho^2 c}{\mu k}$	
A	Area of heat-transfer surface	sq ft
c	Specific heat at constant pressure	Btu/(lb)(deg F)
C	A constant	
d	Differential	
d	Thickness	ft
D	Diameter	ft
e	Length of an edge	ft
e	Base of natural log (2.718)	
E	Total emissive power	Btu/(hr)(sq ft)
f	Friction factor	
f	Function of	
F	Degrees Fahrenheit	deg F
g	Acceleration of gravity	ft/sec^2 and ft per hr^2
G	Mass velocity (V_ρ)	lb/(hr)(sq ft)
Gr	Grashof number $\frac{g\beta\theta L^3\rho^2}{\mu^2}$	
h	Surface coefficient	Btu/(hr)(sq ft)(deg F)
h_c	Surface coefficient of convection	Btu/(hr)(sq ft)(deg F)
h_r	Surface coefficient of radiation	Btu/(hr)(sq ft)(deg F)
I	Radiation intensity	Btu/(hr)(sq ft)
k	Thermal conductivity	Btu/(hr)(sq ft)(deg F/ft)
L	Length	ft
M	Mass	lb
n	Number	
N	Number	
Nu	Nusselt number $\frac{h_c D}{k}$	
p	Emissivity	
Pr	Prandtl number $\frac{c\mu}{k}$	
q	Time rate of heat transfer	Btu/hr
q	Time rate of heat transfer per unit area	Btu/(hr)(sq ft)
Q	Total quantity of heat transferred	Btu
r	Radius	ft
r	Reflectivity	
r	Latent heat of vaporization	Btu/lb
Re	Reynolds number $\frac{DV_\rho}{\mu}$	
S	Surface	sq ft
t	Temperature	deg F
T	Absolute temperature (t + 460)	deg F abs
U	Transmittance (over-all coefficient)	Btu/(hr)(sq ft)(deg F)

Table 1-1. ***(Continued)***

Symbol	Quantity	Units
V	Velocity	ft/hr
W	Weight	lb
x	Thickness	ft
x, y, z	Rectangular coordinates	
α	A constant	
α	Thermal diffusivity	ft^2/hr
β	Coefficient of expansion	1/deg F abs (for gases)
γ	Ratio of specific heats $\frac{c_p}{c_p}$	
Δ	Difference	
θ	Temperature difference	deg F
θ	An angle	
λ	Wave length	microns
μ	Absolute viscosity	lb (mass)/ft hr
μ	Microns, 0.0001 cm	
ν	Frequency	1/sec
π	3.14159	
ρ	Density	lb/cu ft
Σ	Summation of	
σ	Stefan-Boltzmann constant, 0.174×10^{-8}	
ϕ	Function of	
ψ	Function of	
ψ	An angle	

Source: From Brown and Marco, *Introduction To Heat Transfer*. New York: McGraw-Hill, 1942, pp. XIV–XV.

The basic concept of heat transfer is that heat is transferred from a higher temperature to a lower temperature, but never from a lower temperature to a higher temperature. In the case of fire, heat is released to all objects at lower temperatures. To prevent heat transmission, low heat transmission bodies are placed between the fire and the bodies to be protected.

Heat flows primarily via three mechanisms—radiation, conduction, and convection. Each method of heat transfer will be examined individually to improve the understanding of the principles. In fact, actual conditions show that heat often flows simultaneously via these three mechanisms. The reason for calculating heat transfer by three separate mechanisms is that even with a fixed difference in temperature between the two regions, different quantities of heat may be transferred when variations are made in any factor that effects any one of the three mechanisms independently. That is, conduction problems may involve radiation and convection, and convection problems may involve conduction and radiation. When dealing with fire related problems, it is often necessary to determine the quantity of heat transferred by each mechanism. Although much of the investigation of heat transfer in fire is at a high academic level, all of the questions have not yet been answered. There are still years of work required to fully understand all of the principles.

Very often the overall coefficient of heat transmission U, (the quantity of heat transmitted per unit area in a unit time for a difference of 1 °F in the temperatures of the hotter and cooler mediums), is used in the calculations. When heat is transferred to a solid, usually via a fluid, the thermal conditions of the fluid are changed, and in turn, react on the solid surface, via conductance. The surface conductance, when expressed in Btu/h/ft^2 of surface for a difference of 1 °F in the temperatures of the fluid and the adjacent surface, is known as the *surface coefficient* or *film coefficient*, and is denoted by the symbol n.

For solid materials, the coefficient of thermal conductivity K, represents the quantity of heat transmitted via conduction in Btu/hr, from 1 ft^2 of surface area on one side of the solid, to an equal amount of surface area on the other side of the solid 1 ft (may also be expressed as inch) distance, for a temperature change of 1 °F. With a thickness of X ft (may also be expressed as inch) for a solid, k/x represents the heat transmitted in Btu/(hr)(ft^2)(°F).

Heat flow through a unit area of the surface is represented by q the flow through the three barriers (outside film coefficient-solid-inside film coefficient) is represented by:

$$q = h_1(t_1 - t_2) \tag{1.1}$$

$$q = \frac{k}{x}(t_2 - t_3) \tag{1.2}$$

and

$$q = h_2(t_3 - t_4) \tag{1.3}$$

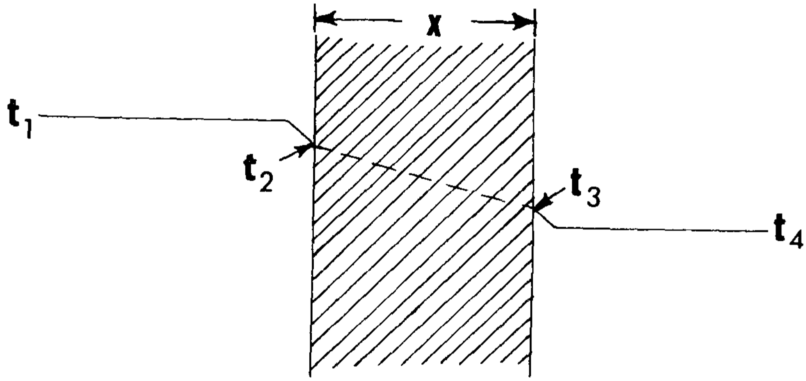

Figure 1-1. Heat flow through a solid.

h_1 and h_2 = Surface coefficients for the two surfaces
k = Coefficient of thermal conductivity
x = Thickness of solid

another method is

$$q = U(t_1 - t_4) \tag{1.4}$$

U = Overall coefficient of heat transmission

When three out of the four terms are known (consider k/x as one term), the other term can then be calculated. These equations can be used to determine temperatures, film coefficients, and any of the other expressions.

RADIATION

Radiation is the transfer of heat from one body to another without temperature change of the intervening medium. If one stands in front of a fire, there is a warm sensation not due to the temperature of the air. This can be proven by placing a screen between the fire and the body whereby the sensation immediately disappears. If the air was heated, this would not happen.

All radiant energy may be regarded as a form of wave motion, known as an electromagnetic phenomenon. These waves are not to be confused with sound waves, vibrations or elastic-mechanical waves. Radiant energy waves can be transmitted through a vacuum.

Wave Length Energy Distribution

A body under controlled conditions will emit radiation at different wave lengths with the energy intensity in each wave length varying. The type of radiation emitted from a body is characterized by the the band of wave lengths having the greatest intensity. A radiation wave will travel at velocity V, which depends on the fluid it is flowing through. The frequency of radiation ν is dependent only on the source; it does not vary with the medium. The ratio $V/\nu = \lambda$ is called the wave length of radiation.

Radiation problems very often refer to a black body, which is a body that emits the maximum possible radiation at a given temperature. The description black, however, has nothing to do with color.

There are several relationships which can be made between temperature and λm (the wave length where maximum energy emission occurs), namely, an increase in temperature T causes a decrease in λm, and a rapid increase in energy emission at any given wave length (the rate of energy emission at λm is called E_m). The total rate of energy emission at any temperature, and for any range of wave lengths, is determined by the area under the curve for that temperature, taken over the wave length range being considered.

Factors About Radiation

It has been proven through experimentation that the higher the temperature of a body, the faster it radiates heat energy. Conversely, any body that has been reduced to absolute zero will not emit thermal radiation. In addition the quantity of heat radiated per unit time is proportional to the amount of exposed surface, and surface finishes will also effect the rates of radiation.

Every surface of a body emits radiation, as does each particle within a body. The internal radiant energy, however, does not reach the surface of the body and only the surface, or some very small distance from the surface, emits a considerable amount of radiant energy. Moreover, the distance beneath the surface, from which radiant eneregy can escape, is limited by the transparency of the body. Transparency is used to define the ease with which all thermal radiation passes through a substance, with some substances transparent to radiation of one wave length and opaque to radiation of another length. Solids are usually opaque to nearly all thermal radiation, and therefore the emission or absorption of radiation takes place within a very thin surface layer. Glass is an exception as are gases, liquids, and some solids.

Radiant Transmission, Absorption and Reflection

When radiant energy strikes a body, it can be absorbed, reflected, or transmitted; and sometimes a combination occurs whereby an opaque body (opaque to thermal radiation) absorbs and reflects all the radiation falling on it.

Radiation incident on an opaque body,

$$qa + qr = qt \tag{1.5}$$

$$\frac{qr}{qt} = r \qquad \frac{qa}{qt} = a$$

$$a + r = 1$$

qa = Radiation absorbed
qr = Radiation reflected
qt = Radiation incident
a = Absorptivity
r = Reflectivity

Reflectivity depends on the character of the surface. Therefore, by treating the surface of an opaque body, the amount of radiant energy absorbed can be either increased or decreased.

Radiation that strikes a transparent body will be absorbed, reflected, and transmitted. This relationship is expressed as follows:

$$qa + qr + qtr = qt \tag{1.6}$$

$$\frac{qa}{qt} = a \qquad \frac{qr}{qt} = r$$

and

$$\frac{qtr}{qt} = tr$$

tr = transmissivity (fraction of incident radiation transmitted through the body)

CONCEPTS AND DEFINITIONS

The total emissive power (E) of a body is the total radiant energy emitted per unit area of radiating surface. The units are usually Btu/(hr)(ft^2) Figure 1-2 shows that E, for any particular temperature, is the area under the curve for that temperature, from λ (wave length in microns) = λ = ∞ or

$$E = \sum_{\lambda = 0}^{\lambda = \infty} E\lambda d\lambda \quad (1.6)$$

where $E\lambda$ is defined as the *monochromatic emissive power*. An example of $E\lambda$ is the release of radiant energy emitted by a body at a particular temperature and wave length.

There does not exist a body for which the reflectivity r is zero, or the absorptivity a is unity. Therefore, no body can absorb all the radiant energy incident upon it. Bodies such as lampblack and platinum reflect only a very small fraction of the incident radiation and are called *black*, but have no relationship to the color. A perfect *black body* is one whose surface absorbs all the radiant energy incident upon it. A black body has $a = 1$ and $r = o$ (a is absorptivity and r is reflectivity).

As previously stated, there is no black body, but for theoretical considerations one will be assumed. If a hole is cut into a cylindrical tube, and a ray of radiant energy enters the tube through the hole, it will be partially absorbed as it strikes the inside surface. Only a small portion of the diffusely reflected energy will find its way through the hole; the rest will be completely absorbed by successive reflections. Upon heating the enclosure, the inside walls radiate energy, and that which passes out of the hole is called black body radiation.

In 1900 Max Planck derived an equation to describe $E\lambda$:

$$E\lambda = \frac{1.16 \times 10^8 \lambda^{-5}}{e^{25740/\lambda T - 1}} \quad (\text{Btu}/(\text{ft}^2)(\text{hr})(u)) \quad (1.7)$$

where

$E\lambda$ = monochromatic emissive power of a black body (Btu/(ft^2)(hr)(u))
λ = Wavelength, u

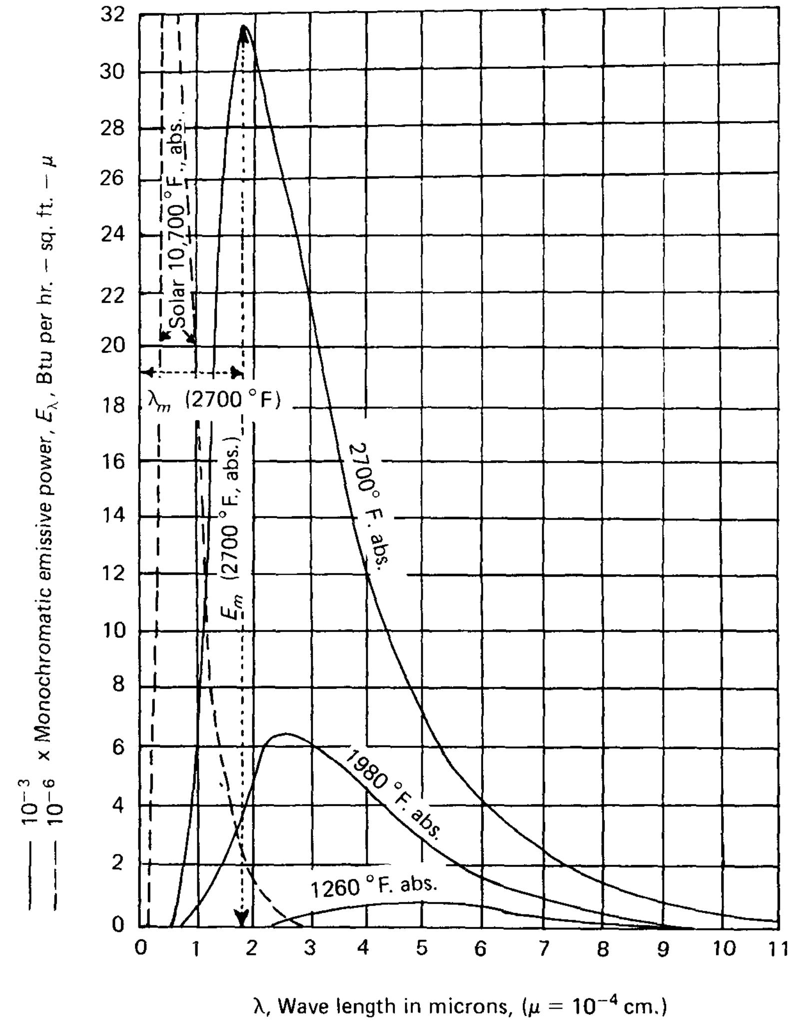

Figure 1-2. Energy distribution of a black body.

T = Temperature of the radiating black body (°R)
e = Napierian base of logarithms which is numerically equal to 2.718

Planck's formula is accepted as an exact relationship between E, λ and T for black body radiation.

When the right hand of equation (1.7) is multiplied by $d\lambda$ and integrated between the limits $\lambda = 0$ to $\lambda = \infty$, it yields the Stefan-Boltzmann law:

$$E_B = 0.174 \times 10^{-8} \times T^4(\text{Btu/ft}^2)(\text{hr})) \qquad (1.8)$$

Table 1-2. The Normal Total Emissivity of Various Surfaces. ***(From Hottel)***

Surfaces	Deg F	p
A. Metals and Their Oxides		
Aluminum:		
Highly polished plate, 98.3% pure	440, 1070	0.039, 0.057
Polished plate	73	0.040
Rough plate	78	0.055
Oxidized at 1110°F	390, 1110	0.11, 0.19
Al-surfaced roofing	110	0.216
Al-treated surfaces, heated at 1110°F:		
Copper	390, 1110	0.18, 0.19
Steel	390, 1110	0.52, 0.57
Brass:		
Highly polished:		
73.2% Cu, 26.7% Zn, by weight	476, 674	0.028, 0.031
62.4% Cu, 36.8% Zn, 0.4% Pb, 0.3% Al, by weight	494, 710	0.0388, 0.037
82.9% Cu, 17.0% Zn, by weight	530	0.030
Hard rolled, polished, but direction of polishing visible	70	0.038
But somewhat attacked	73	0.043
But traces of stearin from polish left on	75	0.053
Polished	100, 600	0.096, 0.096
Rolled plate:		
Natural surface	72	0.06
Rubbed with coarse emery	72	0.20
Dull plate	120, 660	0.22
Oxidized by heating at 1110°F	390, 1110	0.61, 0.59
Chromium:		
See Nickel Alloys for Ni-Cr steels		
Copper:		
Carefully polished electrolytic Cu	176	0.018
Commercial, emeried, polished, but pits remaining	66	0.030
Scraped shiny, but not mirrorlike	72	0.072
Polished	242	0.023
Plate heated at 1110°F	390, 1110	0.57, 0.57
Cuprous oxide	1470, 2010	0.66, 0.54
Plate, heated for a long time, covered with thick oxide layer	77	0.78
Molten copper	1970, 2330	0.16, 0.13
Gold:		
Pure, highly polilshed	440, 1160	0.018, 0.035
Iron and steel:		
Metallic surfaces (or very thin oxide layer):		
Electrolytic iron, highly polished	350, 440	0.052, 0.074
Polished iron	800, 1880	0.144, 0.377
Iron freshly emeried	68	0.242
Cast iron, polished	392	0.21
Wrought iron, highly polished	100, 480	0.28
Cast iron, newly turned	72	0.435
Polished steel casting	1420, 1900	0.52, 0.56
Ground sheet steel	1720, 2010	0.55, 0.61

Table 1-2. (*Continued*)

Surface	Deg F	p
A. Metals and Their Oxides (*Continued*)		
Iron and steel: (*Continued*):		
Smooth sheet iron	1650, 1900	0.55, 0.60
Cast iron, turned on lathe	1620, 1810	0.60, 0.70
Oxidized surfaces:		
Iron plate, pickled, then rusted red	68	0.612
Then completely rusted	70	0.685
Rolled sheet steel	70	0.657
Oxidized iron	212	0.736
Cast iron, oxidized at 1100°F	390, 1110	0.64, 0.78
Steel oxidized at 1100°F	390, 1110	0.79, 0.79
Smooth, oxidized electrolytic iron	260, 980	0.78, 0.82
Iron oxide	930, 2190	0.85, 0.89
Rough ingot iron	1700, 2040	0.87, 0.95
Sheet steel, strong rough oxide layer	75	0.80
Dense shiny oxide layer	75	0.82
Cast plate:		
Smooth	73	0.80
Rough	73	0.82
Cast iron, rough, strongly oxidized	100, 480	0.95
Wrought iron, dull oxidized	70, 680	0.94
Steel plate, rough	100, 700	0.94, 0.97
High-temperature alloy steels; see Nickel Alloys		
Molten metals:		
Molten cast iron	2370, 2550	0.29, 0.29
Molten mild steel	2910, 3270	0.28, 0.28
Lead:		
Pure (99.96%) unoxidized	260, 440	0.057, 0.075
Gray oxidized	75	0.281
Oxidized at 390°F	390	0.63
Mercury, pure clean	32, 212	0.09, 0.12
Molybdenum filament	1340, 4700	0.096, 0.292
Ni-Cu alloy, oxidized at 1110°F	390, 1110	0.41, 0.46
Nickel:		
Electroplated on polished iron, then polished	74	0.045
Technically pure (98.9% Ni by weight, + Mn), polished	440, 710	0.07, 0.087
Electroplated on pickled iron, not polished	68	0.11
Wire	368, 1844	0.096, 0.186
Plate, oxidized by heating at 1110°F	390, 1110	0.37, 0.48
Nickel oxide	1200, 2290	0.59, 0.86
Nickel alloys:		
Cr-Ni alloy	125, 1894	0.64, 0.76
(18-32% Ni, 55-68% Cu, 20% Zn by weight), gray oxidized	70	0.262
Alloy steel (8% Ni, 18% Cr), light silvery rough; brown after heating	420, 914	0.44, 0.36
Same, after 24 hr heating at 980°F	420, 980	0.62, 0.73
Alloy (20% Ni, 25% Cr), brown, splotched, oxidized from service	420, 980	0.90, 0.97