Fermilab

SDC SOLENOID DESIGN NOTE #148

TITLE: Radiation Thickness of Aluminum Alloys

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DATE: July 8, 1991

ABSTRACT: The radiation length of several aluminum alloys was calculated using the chemical composition limits given by the Aluminum Association. The radiation length for 100% Al is 8.893 cm, which is rounded up to 8.9 cm in the Physics Letters table. The radiation length for 2219 is lower because of the copper content, 7.906 cm. The radiation lengths of 5083 and 6061 are 8.900 and 8.753 cm, respectively.

Calculate X_0 for Elements

Reference: Physics Letters B 239:III.5-7 (12 April 1990); see Appendix 1.

The radiation length for some elements, in both g/cm^2 and cm, is given in the table, "Atomic and Nuclear Properties of Materials", in the above reference. Some of the elemental constituents of aluminum alloys are not in this table. An equation to calculate the radiation length of an element from the atomic number and atomic weight is given on Page III.7. However, this equation does not give exactly the values in the table. I used the equation to calculate the radiation length in g/cm^2 for the elements in the table and found an average normalizing factor. I used this factor with the calculated values for other elements to come up with a self-consistent set of values.

The equation (Equation 12 on page III.7) is:

$$X_0 \ (\mathrm{g/cm^2}) = 716.4 \ A/Z(Z + 1)\ln(287/\sqrt{Z}).$$

I substituted A and Z for the alloying elements into this equation, getting the individual radiation lengths shown in the table on the next page.

Element	A	Z	Calc. X_0 g/cm^2	Table X_0 g/cm^2	$\frac{\text{Table } X_0}{\text{Calc. } X_0}$	Final X_0 g/cm^2
Mg	24.32	12	25.29	---	---	24.86
Al	26.98	13	24.26	24.01	0.9897	24.01
Si	28.09	14	22.08	21.82	0.9882	21.82
Ti	47.88	22	16.48	16.17	0.9812	16.17
V	50.95	23	16.15	---	---	15.88
Cr	52.01	24	15.26	---	---	15.00
Mn	54.93	25	14.95	---	---	14.70
Fe	55.85	26	14.14	13.84	0.9788	13.84
Cu	63.55	29	13.16	12.86	0.9772	12.86
Zn	65.38	30	12.72	---	---	12.50
Zr	91.22	40	10.44	---	---	10.27
			Average factor		0.9830	

Calculate X_0 for Aluminum Alloys

Equation for Radiation Length of Mixtures

An equation for calculating the radiation length of mixtures and compounds is given as Equation 13 on page III.7 of the reference:

$$1/X_0 \ (\text{g/cm}^2) = \Sigma \ f_i/X_i,$$

where X_0 = radiation length of mixture or compound, in g/cm^2
f_i = weight fraction of i-th component of the mixture
X_i = radiation length in g/cm^2 of i-th component of mixture.

The radiation length in cm is calculated by dividing the radiation length in g/cm^2 by the density in g/cm^3.

Radiation Length of Pure Aluminum

From the above table $X_0(\text{Al}) = 24.01$ g/cm^2 = 8.893 cm, $\rho = 2.70$ g/cm^3. The table rounds this value off to 8.9 cm.

Radiation Length of Aluminum Alloy 2219

The chemical composition of aluminum alloys is taken from Table 6.2, pg 97 of the "Aluminum Standards and Data, 1990", published by The Aluminum Association, Inc. A photocopy of this table is attached as Appendix 2. The densities of aluminum alloys are found as Table 2.4, pg 43 of this reference (Appendix 3).

Element	f_i	X_i
Si	0.002	21.82
Fe	0.003	13.84
Cu	0.068	12.86
Mn	0.004	14.70
Mg	0.0002	24.86
Zn	0.001	12.50
Ti	0.001	16.17
V	0.0015	15.88
Zr	0.0025	10.27
V	0.0015	15.88
Zr	0.0025	10.27
Al	0.9168	24.01

$$1/X_0(2219) = \Sigma f_i X_i = 0.04454 \text{ cm}^2/\text{g}; \; X_0(2219) = 22.452 \text{ g/cm}^2$$

The density of 2219 is 2.84 g/cm^3, so $X_0(2219) = 7.906$ cm.

Radiation Length of Aluminum Alloy 5083

Element	f_i	X_i
Si	0.004	21.82
Fe	0.004	13.84
Cu	0.001	12.86
Mn	0.010	14.70
Mg	0.049	24.86
Cr	0.0025	15.00
Zn	0.0025	12.50
Ti	0.0015	16.17
Others	0.0015	15.00, assumed
Al	0.9255	24.01

$$1/X_0(5083) = \Sigma f_i X_i = 0.04224 \text{ cm}^2/\text{g}; \; X_0(5083) = 23.672 \text{ g/cm}^2$$

The density of 5083 is 2.66 g/cm^3, so $X_0(5083) = 8.900$ cm.

Radiation Length of Aluminum Alloy 6061

Element	f_i	X_i
Si	0.008	21.82
Fe	0.007	13.84
Cu	0.004	12.86
Mn	0.0015	14.70
Mg	0.012	24.86
Cr	0.0035	15.00
Zn	0.0025	12.50
Ti	0.0015	16.17
Others	0.0015	15.00, assumed
Al	0.9585	24.01

$$1/X_0(6061) = \Sigma f_i X_i = 0.04232 \text{ cm}^2/\text{g}; \; X_0(6061) = 23.632 \text{ g/cm}^2$$

The density of 6061 is 2.70 g/cm^3, so $X_0(6061) = 8.753$ cm.

Comparison of Radiation Lengths of Aluminum Alloys

Alloy	X_0 g/cm^2	X_0 cm	ρ g/cm^3	$\frac{X_0(\text{alloy}) \text{ in cm}}{X_0(\text{pure Al}) \text{ in cm}}$
Pure Al	24.01	8.893	2.70	1.000
2219	22.452	7.906	2.84	0.8890
5083	23.672	8.900	2.66	1.0008
6061	23.632	8.753	2.70	0.9843

Appendix 1

ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS*

Material	Z	A	Nuclear[a] total cross section σ_T [barn]	Nuclear[b] inelastic cross section σ_I [barn]	Nuclear[c] collision length λ_T [g/cm^2]	Nuclear[c] interaction length λ_I [g/cm^2]	$\left.\frac{dE}{dx}\right\|_{min}$[d] $\left[\frac{\text{MeV}}{\text{g/cm}^2}\right]$	Radiation length[e] X_0 [g/cm^2] () is for gas	[cm]	Density[f] [g/cm^3] () is for gas [g/ℓ]	Refractive index n[f] () is $(n-1)\times10^6$ for gas
H_2	1	1.01	0.0387	0.033	43.3	50.8	4.12	61.28	865	0.0708(0.090)	1.112(140)
D_2	1	2.01	0.073	0.061	45.7	54.7	2.07	122.6	757	0.162(0.177)	1.128
He	2	4.00	0.133	0.102	49.9	65.1	1.94	94.32	755	0.125(0.178)	1.024(35)
Li	3	6.94	0.211	0.157	54.6	73.4	1.58	82.76	155	0.534	—
Be	4	9.01	0.268	0.199	55.8	75.2	1.61	65.19	35.3	1.848	—
C	6	12.01	0.331	0.231	60.2	86.3	1.78	42.70	18.8	2.265[g]	—
N_2	7	14.01	0.379	0.265	61.4	87.8	1.82	37.99	47.0	0.808(1.25)	1.205(300)
O_2	8	16.00	0.420	0.292	63.2	91.0	1.82	34.24	30.0	1.14(1.43)	1.22(266)
Ne	10	20.18	0.507	0.347	66.1	96.6	1.73	28.94	24.0	1.207(0.90)	1.092(67)
Al	13	26.98	0.634	0.421	70.6	106.4	1.62	24.01	8.9	2.70	—
Si	14	28.09	0.660	0.440	70.6	106.0	1.66	21.82	9.36	2.33	—
Ar	18	39.95	0.868	0.566	76.4	117.2	1.51	19.55	14.0	1.40(1.78)	1.233(283)
Ti	22	47.88	0.995	0.637	79.9	124.9	1.51	16.17	3.56	4.54	—
Fe	26	55.85	1.120	0.703	82.8	131.9	1.48	13.84	1.76	7.87	—
Cu	29	63.55	1.232	0.782	85.6	134.9	1.44	12.86	1.43	8.96	—
Ge	32	72.59	1.365	0.858	88.3	140.5	1.40	12.25	2.30	5.323	—
Sn	50	118.69	1.967	1.21	100.2	163	1.26	8.82	1.21	7.31	—
Xe	54	131.29	2.120	1.29	102.8	169	1.24	8.48	2.77	3.057(5.89)	(705)
W	74	183.85	2.767	1.65	110.3	185	1.16	6.76	0.35	19.3	—
Pt	78	195.08	2.861	1.708	113.3	189.7	1.15	6.54	0.305	21.45	—
Pb	82	207.19	2.960	1.77	116.2	194	1.13	6.37	0.56	11.35	—
U	92	238.03	3.378	1.98	117.0	199	1.09	6.00	≈0.32	≈18.95	—
Air, 20°C, 1 atm. (STP in paren.)					62.0	90.0	1.82	36.66	(30420)	0.001205(1.29)	1.000273(293)
H_2O					60.1	84.9	2.03	36.08	36.1	1.00	1.33
Shielding concrete[h]					67.4	99.9	1.70	26.7	10.7	2.5	—
SiO_2 (quartz)					67.0	99.2	1.72	27.05	12.3	2.64	1.458
H_2 (bubble chamber 26°K)					43.3	50.8	4.12	61.28	≈1000	≈ 0.063[i]	1.100
D_2 (bubble chamber 31°K)					45.7	54.7	2.07	122.6	≈900	≈ 0.140[i]	1.110
H-Ne mixture (50 mole percent)[j]					65.0	94.5	1.84	29.70	73.0	0.407	1.092
Ilford emulsion G5					82.0	134	1.44	11.0	2.89	3.815	—
NaI					94.8	152	1.32	9.49	2.59	3.67	1.775
BaF_2					92.1	146	1.35	9.91	2.05	4.89	1.56
BGO ($Bi_4Ge_3O_{12}$)					97.4	156	1.27	7.98	1.12	7.1	2.15
Polystyrene, scintillator (CH)[k]					58.4	82.0	1.95	43.8	42.4	1.032	1.581
Lucite, Plexiglas ($C_5H_8O_2$)					59.2	83.6	1.95	40.55	≈34.4	1.16–1.20	≈ 1.49
Polyethylene (CH_2)					56.9	78.8	2.09	44.8	≈47.9	0.92–0.95	—
Mylar ($C_5H_4O_2$)					60.2	85.7	1.86	39.95	28.7	1.39	—
Borosilicate glass (Pyrex)[ℓ]					66.2	97.6	1.72	28.3	12.7	2.23	1.474
CO_2					62.4	90.5	1.82	36.2	(18310)	(1.977)	(410)
Ethane C_2H_6					55.73	75.71	2.25	45.66	(34035)	0.509(1.356)[m]	(1.038)[m]
Methane CH_4					54.7	74.0	2.41	46.5	(64850)	0.423(0.717)	(444)
Isobutane C_4H_{10}					56.3	77.4	2.22	45.2	(16930)	(2.67)	(1270)
NaF					66.78	97.57	1.69	29.87	11.68	2.558	1.336
LiF					62.00	88.24	1.66	39.25	14.91	2.632	1.392
Freon 12 (CCl_2F_2) gas, 26°C, 1 atm.[n]					70.6	106	1.62	23.7	4810	(4.93)	1.001080
Silica Aerogel[o]					65.5	95.7	1.83	29.85	≈150	0.1–0.3	$1.0+0.25\rho$
NEMA G10 plate[p]					62.6	90.2	1.87	33.0	19.4	1.7	—

ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS (Cont'd)

Material	Dielectric constant ($\kappa = \epsilon/\epsilon_0$) () is $(\kappa-1)\times10^6$ for gas	Young's modulus [10^6 psi]	Coeff. of thermal expansion [10^{-6}cm/cm-°C]	Specific heat [cal/g-°C]	Electrical resistivity [$\mu\Omega$cm(@°C)]	Thermal conductivity [cal/cm-°C-sec]
H_2	(253.9)	—	—	—	—	—
He	(64)	—	—	—	—	—
Li	—	—	56	0.86	8.55(0°)	0.17
Be	—	37	12.4	0.436	5.885(0°)	0.38
C	—	0.7	0.6–4.3	0.165	1375(0°)	0.057
N_2	(548.5)	—	—	—	—	—
O_2	(495)	—	—	—	—	—
Ne	(127)	—	—	—	—	—
Al	—	10	23.9	0.215	2.65(20°)	0.53
Si	11.9	16	2.8–7.3	0.162	—	0.20
Ar	(517)	—	—	—	—	—
Ti	—	16.8	8.5	0.126	50(0°)	—
Fe	—	28.5	11.7	0.11	9.71(20°)	0.18
Cu	—	16	16.5	0.092	1.67(20°)	0.94
Ge	16.0	—	5.75	0.073	—	0.14
Sn	—	6	20	0.052	11.5(20°)	0.16
Xe	—	—	—	—	—	—
W	—	50	4.4	0.032	5.5(20°)	0.48
Pt	—	21	8.9	0.032	9.83(0°)	0.17
Pb	—	2.6	29.3	0.038	20.65(20°)	0.083
U	—	—	36.1	0.028	29(20°)	0.064

* Table revised April 1988 by R.W. Kenney. σ_T, σ_I, λ_T, and λ_I are energy dependent. Values quoted apply to high energy range given in footnote *a* or *b*, where energy dependence is weak.

a. σ_{total} at 80–240 GeV for neutrons ($\approx\sigma$ for protons) from Murthy *et al.*, Nucl. Phys. **B92**, 269 (1975). This scales approximately as $A^{0.77}$.

b. $\sigma_{\text{inelastic}} = \sigma_{\text{total}} - \sigma_{\text{elastic}} - \sigma_{\text{quasielastic}}$; for neutrons at 60–375 GeV from Roberts *et al.*, Nucl. Phys. **B159**, 56 (1979). For protons and other particles, see Carroll *et al.*, Phys. Lett. **80B**, 319 (1979); note that $\sigma_I(p) \approx \sigma_I(n)$. σ_I scales approximately as $A^{0.71}$.

c. Mean free path between collisions (λ_T) or inelastic interactions (λ_I), calculated from $\lambda = A/(N \times \sigma)$, where N is Avogadro's number.

d. For minimum-ionizing protons and pions from Barkas and Berger, *Tables of Energy Losses and Ranges of Heavy Charged Particles*, NASA-SP-3013 (1964). For electrons and positrons see: M.J. Berger and S.M. Seltzer, *Stopping Powers and Ranges of Electrons and Positrons* (2nd Ed.), U.S. National Bureau of Standards report NBSIR 82-2550-A (1982).

e. From Y.S. Tsai, Rev. Mod. Phys. **46**, 815 (1974); X_0 data for all elements up to uranium may be found here. Corrections for molecular binding applied for H_2 and D_2. Parentheses refer to gaseous form at STP (0°C, 1 atm.).

f. Values for solids, or the liquid phase at boiling point, except as noted. Values in parentheses for gaseous phase at STP (0°C, 1 atm.). Refractive index given for sodium *D* line.

g. For pure graphite; industrial graphite density may vary 2.1–2.3 g/cm^3.

h. Standard shielding blocks, typical composition O_2 52%, Si 32.5%, Ca 6%, Na 1.5%, Fe 2%, Al 4%, plus reinforcing iron bars. The attenuation length, $\ell = 115 \pm 5$ g/cm^2, is also valid for earth (typical $\rho = 2.15$), from CERN-LRL-RHEL Shielding exp., UCRL-17841 (1968).

i. Density may vary about ±3%, depending on operating conditions.

j. Values for typical working conditions with H_2 target: 50 mole percent, 29°K, 7 atm.

k. Typical scintillator; e.g., PILOT B and NE 102A have an atomic ratio H/C = 1.10.

ℓ. Main components: 80% SiO_2 + 12% B_2O_3 + 5% Na_2O.

m. Solid ethane density at −60°C; gaseous refractive index at 0°C, 546 mm pressure.

n. Used in Čerenkov counters. Values at 26°C and 1 atm. Indices of refraction from E.R. Hayes, R.A. Schluter, and A. Tamosaitis, ANL-6916 (1964).

o. $n(SiO_2) + 2n(H_2O)$ used in Čerenkov counters, ρ = density in g/cm^3. From M. Cantin *et al.*, Nucl. Instr. and Meth. **118**, 177 (1974).

p. G10-plate, typical 60% SiO_2 and 40% epoxy.

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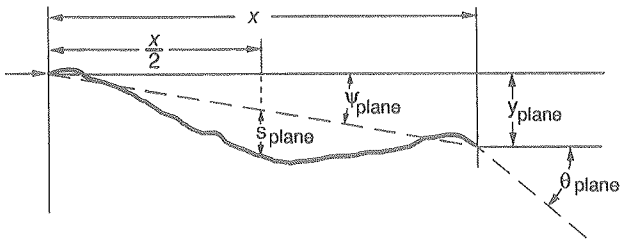

Fig. 1. Quantities useful in describing multiple Coulomb scattering. The particle is incident in the plane of the figure.

for the definition of the correlation coefficient). Obviously, $y \approx x\psi$. In addition, y and θ have correlation coefficient $\rho_{y\theta} = \sqrt{3}/2 \approx 0.87$. For Monte Carlo generation of a joint $(y_{\text{plane}}, \theta_{\text{plane}})$ distribution or for other calculations, it may be most convenient to work with independent Gaussian random variables (z_1, z_2) with mean zero and variance one and subsequently set

$$\begin{aligned} y_{\text{plane}} &= z_1\, x\, \theta_0 (1-\rho^2_{y\theta})^{1/2}/\sqrt{3} + z_2\, \rho_{y\theta}\, x\, \theta_0/\sqrt{3} \\ &= z_1\, x\, \theta_0/\sqrt{12} + z_2\, x\, \theta_0/2\ ; \\ \theta_{\text{plane}} &= z_2\, \theta_0\ . \end{aligned} \tag{11}$$

Note that the second term for y_{plane} equals $x\,\theta_{\text{plane}}/2$ and represents the displacement that would have occurred had the deflection θ_{plane} all occurred at the single point $x/2$.

(7) Radiation length and associated quantities: In dealing with electrons and photons at high energies, it is convenient to measure the thickness of the material in units of the radiation length X_0. It is the mean distance over which a high-energy electron loses all but $1/e$ of its energy by bremsstrahlung, and in any case it is the appropriate scale length for describing high-energy electromagnetic cascades. X_0 is calculated and tabulated by Y.S. Tsai.[18] His formula is less than straightforward, but can be approximated by [19]

$$X_0 = \frac{716.4\ \text{g cm}^{-2}\, A}{Z(Z+1)\ln(287/\sqrt{Z})}\ , \tag{12}$$

where Z is the atomic number and A the atomic weight of the medium. Results obtained with this formula agree with Tsai's values to better than 2.5% for all elements except helium, where the result is low by about 5%. The radiation length in a mixture or compound, may be approximated by

$$\frac{1}{X_0} = \sum \frac{f_i}{X_i}\ , \tag{13}$$

where f_i and X_i are the fraction by weight and radiation length for the ith element.

Radiative energy losses scale nearly proportionally to incident energy, while the dependence of ionization is only logarithmic. The energy at which the two are equal is called the ***critical energy*** E_c. For electrons it is given approximately by[20]

$$E_c = \frac{800\ \text{MeV}}{Z+1.2}\ . \tag{14}$$

In an electromagnetic cascade E_c defines the dividing line between shower multiplication and energy dissipation through ionization.

The transverse development of electromagnetic showers in different materials scales fairly accurately with the *Molière radius* R_M, given by[21]

$$R_M = X_0\, E_s/E_c\ , \tag{15}$$

where $E_s = \sqrt{4\pi/\alpha}\ m_e c^2 = 21.2$ MeV. The Molière radius in a material containing a weight fraction f_i of the element with critical energy E_{ci} and radiation length X_i is given by

$$\frac{1}{R_M} = \frac{1}{E_s} \sum \frac{f_i\, E_{ci}}{X_i}\ . \tag{16}$$

For photons of infinite energy, the total e^+e^- pair-production cross section is approximately

$$\sigma = \tfrac{7}{9}(A/X_0 N_A)\ , \tag{17}$$

where A is the atomic weight of the material and N_A is Avogadro's number. This cross section is accurate to within a few percent down to energies as low as 1 GeV; it decreases at lower energies, as shown in the figure "Fractional Energy Loss for Electrons and Positrons in Lead." As the energy decreases a number of other processes become important, as is also shown in the figures "Contributions to the Photon Cross Section in Carbon and Lead."

(8) Electromagnetic cascades: When a high-energy electron or photon is incident on a thick absorber, it initiates an electromagnetic cascade as pair production and bremsstrahlung generate more electrons and photons with lower energy. The longitudinal development is governed by the high-energy part of the cascade, and therefore scales as the radiation length in the material. Electron energies eventually fall below the critical energy, and they dissipate their energy by ionization and excitation rather than by the generation of more shower particles. In describing shower behavior, it is therefore convenient to introduce the scale variables

$$\begin{aligned} t &= x/X_0 \\ y &= E/E_c\ , \end{aligned} \tag{18}$$

so that distance is measured in units of radiation length and energy in units of critical energy.

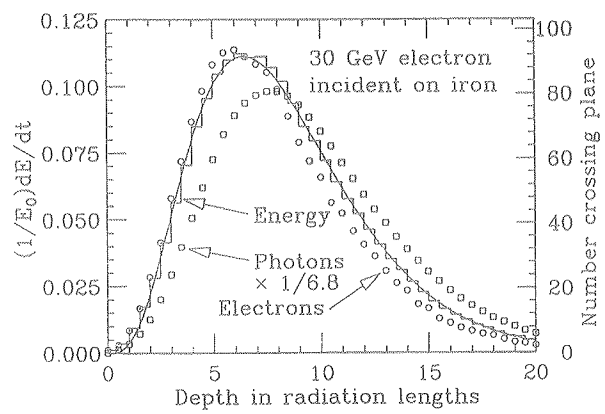

Fig. 2. An EGS4 simulation of a 30 GeV electron-induced cascade in iron. The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution. Circles indicate the number of electrons with total energy greater than 1.5 MeV crossing planes at $X_0/2$ intervals (scale on right) and the squares the number of photons with $E \geq 1.5$ MeV crossing the planes (scaled down to have same area as the electron distribution).

Longitudinal profiles for an EGS4[22] simulation of a 30 GeV electron-induced cascade in iron are shown in Fig. 2. The number of particles crossing a plane (very close to Rossi's $\prod$ function[1]) is sensitive to the cutoff energy, here chosen as a total energy of 1.5 MeV for both electrons and photons. The electron number falls off more quickly than energy deposition; this is because a larger fraction of the cascade energy is carried by photons with increasing depth. Exactly what a calorimeter measures depends on the device, but it is not likely to be exactly any of the profiles shown. In gas counters it may be very close to the electron number, but in glass Čerenkov detectors and other devices with "thick" sensitive regions it is closer to the energy deposition (total track length). In such detectors the signal is proportional to the "detectable" track length T_d, which is in general less than the total track length T. Practical devices are sensitive to electrons with energy above some detection threshold E_d, and

TABLE 6.2 Chemical Composition Limits of Wrought Aluminum Alloys①②

AA DESIG-NATION	SILICON	IRON	COPPER	MAN-GANESE	MAG-NESIUM	CHROM-IUM	NICKEL	ZINC	TITAN-IUM	OTHERS㉒		ALUMI-NUM Min.④
										Each⑳	Total③	
1050	0.25	0.40	0.05	0.05	0.05	. .	. .	0.05	0.03	0.03⑨	. .	99.50
1060	0.25	0.35	0.05	0.03	0.03	. .	. .	0.05	0.03	0.03⑨	. .	99.60
1100	0.95 Si + Fe		0.05–0.20	0.05	. .	. .	. .	0.10	. .	0.05⑯	0.15	99.00
1145⑧	0.55 Si + Fe		0.05	0.05	0.05	. .	. .	0.05	0.03	0.03⑨	. .	99.45
1175⑦	0.15 Si + Fe		0.10	0.02	0.02	. .	. .	0.04	0.02	0.02⑲	. .	99.75
1200	1.00 Si + Fe		0.05	0.05	. .	. .	. .	0.10	0.05	0.05	0.15	99.00
1230⑦	0.70 Si + Fe		0.10	0.05	0.05	. .	. .	0.10	0.03	0.03⑨	. .	99.30
1235	0.65 Si + Fe		0.05	0.05	0.05	. .	. .	0.10	0.06	0.03⑨	. .	99.35
1345	0.03	0.40	0.10	0.05	0.05	. .	. .	0.05	0.03	0.03⑨	. .	99.45
1350⑥	0.10	0.40	0.05	0.01	. .	0.01	. .	0.05	. .	0.03⑬	0.10	99.50
2011	0.40	0.7	5.0–6.0	. .	. .	. .	. .	0.30	. .	0.05⑩	0.15	Remainder
2014	0.05–1.2	0.7	3.9–5.0	0.40–1.2	0.20–0.8	0.10	. .	0.25	0.15	0.05	0.15	Remainder
2017	0.20–0.8	0.7	3.5–4.5	0.40–1.0	0.40–0.8	0.10	. .	0.25	0.15	0.05	0.15	Remainder
2018	0.9	1.0	3.5–4.5	0.20	0.45–0.9	0.10	1.7–2.3	0.25	. .	0.05	0.15	Remainder
2024	0.50	0.50	3.8–4.9	0.30–0.9	1.2–1.8	0.10	. .	0.25	0.15	0.05	0.15	Remainder
2025	0.50–1.2	1.0	3.9–5.0	0.40–1.2	0.05	0.10	. .	0.25	0.15	0.05	0.15	Remainder
2036	0.50	0.50	2.2–3.0	0.10–0.40	0.30–0.6	0.10	. .	0.25	0.15	0.05	0.15	Remainder
2117	0.8	0.7	2.2–3.0	0.20	0.20–0.50	0.10	. .	0.25	. .	0.05	0.15	Remainder
2124	0.20	0.30	3.8–4.9	0.30–0.9	1.2–1.8	0.10	. .	0.25	0.15	0.05	0.15	Remainder
2218	0.9	1.0	3.5–4.5	0.20	1.2–1.8	0.10	1.7–2.3	0.25	. .	0.05	0.15	Remainder
2219	0.20	0.30	5.8–6.8	0.20–0.40	0.02	. .	. .	0.10	0.02–0.10	0.05⑱	0.15	Remainder
2319	0.20	0.30	5.8–6.8	0.20–0.40	0.02	. .	. .	0.10	0.10–0.20	0.05⑱	0.15	Remainder
2618	0.10–0.25	0.9–1.3	1.9–2.7	. .	1.3–1.8	. .	0.9–1.2	0.10	0.04–0.10	0.05	0.15	Remainder
3003	0.6	0.7	0.05–0.20	1.0–1.5	. .	. .	. .	0.10	. .	0.05	0.15	Remainder
3004	0.30	0.7	0.25	1.0–1.5	0.8–1.3	. .	. .	0.25	. .	0.05	0.15	Remainder
3005	0.6	0.7	0.30	1.0–1.5	0.20–0.6	0.10	. .	0.25	0.10	0.05	0.15	Remainder
3105	0.6	0.7	0.30	0.30–0.8	0.20–0.8	0.20	. .	0.40	0.10	0.05	0.15	Remainder
4032	11.0–13.5	1.0	0.50–1.3	. .	0.8–1.3	0.10	0.50–1.3	0.25	. .	0.05	0.15	Remainder
4043	4.5–6.0	0.8	0.30	0.05	0.05	. .	. .	0.10	0.20	0.05⑯	0.15	Remainder
4045⑪	9.0–11.0	0.8	0.30	0.05	0.05	. .	. .	0.10	0.20	0.05	0.15	Remainder
4047⑪	11.0–13.0	0.8	0.30	0.15	0.10	. .	. .	0.20	. .	0.05⑯	0.15	Remainder
4145⑪	9.3–10.7	0.8	3.3–4.7	0.15	0.15	0.15	. .	0.20	. .	0.05⑯	0.15	Remainder
4343⑪	6.8–8.2	0.8	0.25	0.10	. .	. .	. .	0.20	. .	0.05	0.15	Remainder
5005	0.30	0.7	0.20	0.20	0.50–1.1	0.10	. .	0.25	. .	0.05	0.15	Remainder
5050	0.40	0.7	0.20	0.10	1.1–1.8	0.10	. .	0.25	. .	0.05	0.15	Remainder
5052	0.25	0.40	0.10	0.10	2.2–2.8	0.15–0.35	. .	0.10	. .	0.05	0.15	Remainder
5056	0.30	0.40	0.10	0.05–0.20	4.5–5.6	0.05–0.20	. .	0.10	. .	0.05	0.15	Remainder
5083	0.40	0.40	0.10	0.40–1.0	4.0–4.9	0.05–0.25	. .	0.25	0.15	0.05	0.15	Remainder
5086	0.40	0.50	0.10	0.20–0.7	3.5–4.5	0.05–0.25	. .	0.25	0.15	0.05	0.15	Remainder
5154	0.25	0.40	0.10	0.10	3.1–3.9	0.15–0.35	. .	0.20	0.20	0.05	0.15	Remainder
5183	0.40	0.40	0.10	0.50–1.0	4.3–5.2	0.05–0.25	. .	0.25	0.15	0.05⑯	0.15	Remainder
5252	0.08	0.10	0.10	0.10	2.2–2.8	. .	. .	0.05	. .	0.03⑨	0.10	Remainder
5254	0.45 Si + Fe		0.05	0.01	3.1–3.9	0.15–0.35	. .	0.20	0.05	0.05	0.15	Remainder
5356	0.25	0.40	0.10	0.05–0.20	4.5–5.5	0.05–0.20	. .	0.10	0.06–0.20	0.05⑯	0.15	Remainder
5454	0.25	0.40	0.10	0.50–1.0	2.4–3.0	0.05–0.20	. .	0.25	0.20	0.05	0.15	Remainder
5456	0.25	0.40	0.10	0.50–1.0	4.7–5.5	0.05–0.20	. .	0.25	0.20	0.05	0.15	Remainder
5457	0.08	0.10	0.20	0.15–0.45	0.8–1.2	. .	. .	0.05	. .	0.03⑨	0.10	Remainder
5554	0.25	0.40	0.10	0.50–1.0	2.4–3.0	0.05–0.20	. .	0.25	0.05–0.20	0.05⑯	0.15	Remainder
5556	0.25	0.40	0.10	0.50–1.0	4.7–5.5	0.05–0.20	. .	0.25	0.05–0.20	0.05⑯	0.15	Remainder
5652	0.40 Si + Fe		0.04	0.01	2.2–2.8	0.15–0.35	. .	0.10	. .	0.05	0.15	Remainder
5654	0.45 Si + Fe		0.05	0.01	3.1–3.9	0.15–0.35	. .	0.20	0.05–0.15	0.05⑯	0.15	Remainder
5657	0.08	0.10	0.10	0.03	0.6–1.0	. .	. .	0.05	. .	0.02⑲	0.05	Remainder

For all numbered footnotes, see page 98.

AA DESIG-NATION	SILICON	IRON	COPPER	MAN-GANESE	MAG-NESIUM	CHROM-IUM	NICKEL	ZINC	TITAN-IUM	OTHERS㉒		ALUMI-NUM Min.④
										Each⑳	Total③	
6003⑦	0.35-1.0	0.6	0.10	0.8	0.8-1.5	0.35	. .	0.20	0.10	0.05	0.15	Remainder
6005	0.6-0.9	0.35	0.10	0.10	0.40-0.6	0.10	. .	0.10	0.10	0.05	0.15	Remainder
6053	⑮	0.35	0.10	. .	1.1-1.4	0.15-0.35	. .	0.10	. .	0.05	0.15	Remainder
6061	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	. .	0.25	0.15	0.05	0.15	Remainder
6063	0.20-0.6	0.35	0.10	0.10	0.45-0.9	0.10	. .	0.10	0.10	0.05	0.15	Remainder
6066	0.9-1.8	0.50	0.7-1.2	0.6-1.1	0.8-1.4	0.40	. .	0.25	0.20	0.05	0.15	Remainder
6070	1.0-1.7	0.50	0.15-0.40	0.40-1.0	0.50-1.2	0.10	. .	0.25	0.15	0.05	0.15	Remainder
6101⑫	0.30-0.7	0.50	0.10	0.03	0.35-0.8	0.03	. .	0.10	. .	0.03⑰	0.10	Remainder
6105	0.6-1.0	0.35	0.10	0.10	0.45-0.8	0.10	. .	0.10	0.10	0.05	0.15	Remainder
6151	0.6-1.2	1.0	0.35	0.20	0.45-0.8	0.15-0.35	. .	0.25	0.15	0.05	0.15	Remainder
6162	0.40-0.8	0.50	0.20	0.10	0.7-1.1	0.10	. .	0.25	0.10	0.05	0.15	Remainder
6201	0.50-0.9	0.50	0.10	0.03	0.6-0.9	0.03	. .	0.10	. .	0.03⑰	0.10	Remainder
6253⑦	⑮	0.50	0.10	. .	1.0-1.5	0.04-0.35	. .	1.6-2.4	. .	0.05	0.15	Remainder
6262	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.14	. .	0.25	0.15	0.05⑤	0.15	Remainder
6351	0.7-1.3	0.50	0.10	0.40-0.8	0.40-0.8	. .	. .	0.20	0.20	0.05	0.15	Remainder
6463	0.20-0.6	0.15	0.20	0.05	0.45-0.9	. .	. .	0.05	. .	0.05	0.15	Remainder
6951	0.20-0.50	0.8	0.15-0.40	0.10	0.40-0.8	. .	. .	0.20	. .	0.05	0.15	Remainder
7005	0.35	0.40	0.10	0.20-0.7	1.0-1.8	0.06-0.20	. .	4.0-5.0	0.01-0.06	0.05⑭	0.15	Remainder
7008⑦	0.10	0.10	0.05	0.05	0.7-1.4	0.12-0.25	. .	4.5-5.5	0.05	0.05	0.10	Remainder
7049	0.25	0.35	1.2-1.9	0.20	2.0-2.9	0.10-0.22	. .	7.2-8.2	0.10	0.05	0.15	Remainder
7050	0.12	0.15	2.0-2.6	0.10	1.9-2.6	0.04	. .	5.7-6.7	0.06	0.05㉑	0.15	Remainder
7072⑦	0.7 Si + Fe		0.10	0.10	0.10	. .	. .	0.8-1.3	. .	0.05	0.15	Remainder
7075	0.40	0.50	1.2-2.0	0.30	2.1-2.9	0.18-0.28	. .	5.1-6.1	0.20	0.05	0.15	Remainder
7175	0.15	0.20	1.2-2.0	0.10	2.1-2.9	0.18-0.28	. .	5.1-6.1	0.10	0.05	0.15	Remainder
7178	0.40	0.50	1.6-2.4	0.30	2.4-3.1	0.18-0.28	. .	6.3-7.3	0.20	0.05	0.15	Remainder
7475	0.10	0.12	1.2-1.9	0.06	1.9-2.6	0.18-0.25	. .	5.2-6.2	0.06	0.05	0.15	Remainder
8017	0.10	0.55-0.8	0.10-0.20	. .	0.01-0.05	. .	. .	0.05	. .	0.03㉓	0.10	Remainder
8030	0.10	0.30-0.8	0.15-0.30	. .	0.05	. .	. .	0.05	. .	0.03㉔	0.10	Remainder
8176	0.03-0.15	0.40-1.0	. .	. .	. .	. .	. .	0.10	. .	0.05㉕	0.15	Remainder
8177	0.10	0.25-0.45	0.04	. .	0.04-0.12	. .	. .	0.05	. .	0.03㉖	0.10	Remainder

Note: Listed herein are designations and chemical composition limits for some wrought unalloyed aluminum and for wrought aluminum alloys registered with The Aluminum Association. This list does not include all alloys registered with The Aluminum Association. A complete list of registered designations is contained in the "Registration Record of International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys." These lists are maintained by the Technical Committee on Product Standards of the Aluminum Association.

① Composition in percent by weight maximum unless shown as a range or a minimum.

② Except for "aluminum" and "others," analysis normally is made for elements for which specific limits are shown. For purposes of determining conformance to these limits, an observed value or a calculated value obtained from analysis is rounded off to the nearest unit in the last right-hand place of figures used in expressing the specified limit, in accordance with ASTM Recommended Practice E 29.

③ The sum of those "other" metallic elements 0.010 percent or more each, expressed to the second decimal before determining the sum.

④ The aluminum content for unalloyed aluminum not made by a refining process is the difference between 100.00 percent and the sum of all other metallic elements present in amounts of 0.010 percent or more each, expressed to the second decimal before determining the sum.

⑤ Also contains 0.40-0.7 percent each of lead and bismuth.

⑥ Electric conductor. Formerly designated EC.

⑦ Cladding alloy. See Table 6.1.

⑧ Foil.

⑨ Vanadium 0.05 percent maximum.

⑩ Also contains 0.20-0.6 percent each of lead and bismuth.

⑪ Brazing alloy.

⑫ Bus conductor.

⑬ Vanadium plus titanium 0.02 percent maximum; boron 0.05 percent maximum; gallium 0.03 percent maximum.

⑭ Zirconium 0.08-0.20

⑮ Silicon 45 to 65 percent of actual magnesium content.

⑯ Beryllium 0.0008 maximum for welding electrode and welding rod only.

⑰ Boron 0.06 percent maximum.

⑱ Vanadium 0.05-0.15; zirconium 0.10-0.25.

⑲ Gallium 0.03 percent maximum; vanadium 0.05 percent maximum.

⑳ In addition to those alloys referencing footnote ⑯, a 0.0008 weight percent maximum beryllium is applicable to any alloy to be used as welding electrode or welding rod.

㉑ Zirconium 0.08-0.15.

㉒ Includes listed elements for which no specific limit is shown.

㉓ Boron 0.04 percent maximum; lithium 0.003 percent maximum.

㉔ Boron 0.001-0.04.

㉕ Gallium 0.03 percent maximum.

㉖ Boron 0.04 percent maximum.

Table 2.4 Nominal Densities of Aluminum and Aluminum Alloys

Density and specific gravity are dependent upon composition, and variations are discernible from one cast to another for most alloys. The nominal values shown below should not be specified as engineering requirements but are used in calculating typical values for weight per unit length, weight per unit area, covering area, etc. The density values are derived from the metric and subsequently rounded. These values are not to be back converted to the metric. X.XXX0 and X.XXX5 density values and X.XX0 and X.XX5 specific gravity values are limited to 99.35 percent or higher purity aluminum.

Alloy	Density (lbs/cu in.)	Specific Gravity
1050	.0975	2.705
1060	.0975	2.705
1100	0.98	2.71
1145	.0975	2.700
1175	.0975	2.700
1200	.098	2.70
1230	.098	2.70
1235	.0975	2.705
1345	.0975	2.705
1350	.0975	2.705
2011	.102	2.83
2014	.101	2.80
2017	.101	2.79
2018	.102	2.82
2024	.101	2.78
2025	.101	2.81
2036	.100	2.75
2117	.099	2.75
2124	.100	2.78
2218	.101	2.81
2219	.103	2.84
2618	.100	2.76
3003	.099	2.73
3004	.098	2.72
3005	.098	2.73
3105	.098	2.72
4032	.097	2.68
4043	.097	2.69
4045	.096	2.67
4047	.096	2.66
4145	.099	2.74
4343	.097	2.68
5005	.098	2.70
5050	.097	2.69
5052	.097	2.68
5056	.095	2.64
5083	.096	2.66
5086	.096	2.66
5154	.096	2.66

Alloy	Density (lbs/cu in.)	Specific Gravity
5183	.096	2.66
5252	.096	2.67
5254	.096	2.66
5356	.096	2.64
5454	.097	2.69
5456	.096	2.66
5457	.097	2.69
5554	.097	2.69
5556	.096	2.66
5652	.097	2.67
5654	.096	2.66
5657	.097	2.69
6003	.097	2.70
6005	.097	2.70
6053	.097	2.69
6061	.098	2.70
6063	.097	2.70
6066	.098	2.72
6070	.098	2.71
6101	.097	2.70
6105	.097	2.69
6151	.098	2.71
6162	.097	2.70
6201	.097	2.69
6262	.098	2.72
6351	.098	2.71
6463	.097	2.69
6951	.098	2.70
7005	.100	2.78
7008	.100	2.78
7049	.103	2.84
7050	.102	2.83
7072	.098	2.72
7075	.101	2.81
7175	.101	2.80
7178	.102	2.83
7475	.101	2.81
8017	.098	2.71
8030	.098	2.71
8176	.098	2.71
8177	.098	2.70