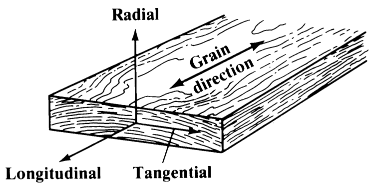
PROPERTIES OF WOOD, CERAMICS, PLASTICS, METALS, WATER, AND AIR

Properties of Wood

Mechanical Properties of Wood.—Wood is composed of cellulose, lignin, ash-forming minerals, and extractives formed into a cellular structure. (Extractives are substances that can be removed from wood by extraction with such solvents as water, alcohol, acetone, benzene, and ether.) Variations in the characteristics and volumes of the four components and differences in the cellular structure result in some woods being heavy and some light, some stiff and some flexible, and some hard and some soft. For a single species, the properties are relatively constant within limits; therefore, selection of wood by species alone may sometimes be adequate. However, to use wood most effectively in engineering applications, the effects of physical properties or specific characteristics must be considered.

The mechanical properties listed in the accompanying table were obtained from tests on small pieces of wood termed "clear" and "straight grained" because they did not contain such characteristics as knots, cross grain, checks, and splits. However, these test pieces did contain such characteristics as growth rings that occur in consistent patterns within the piece. Since wood products may contain knots, cross grain, etc., these characteristics must be taken into account when assessing actual properties or when estimating actual performance. In addition, the methods of data collection and analysis have changed over the years during which the data in the table have been collected; therefore, the appropriateness of the data should be reviewed when used for critical applications such as stress grades of lumber.

Wood is an orthotropic material; that is, its mechanical properties are unique and independent in three mutually perpendicular directions—longitudinal, radial, and tangential. These directions are illustrated in the following figure.



Modulus of Rupture: The modulus of rupture in bending reflects the maximum load-carrying capacity of a member and is proportional to the maximum moment borne by the member. The modulus is an accepted criterion of strength, although it is not a true stress because the formula used to calculate it is valid only to the proportional limit.

Work to Maximum Load in Bending: The work to maximum load in bending represents the ability to absorb shock with some permanent deformation and more or less injury to a specimen; it is a measure of the combined strength and toughness of the wood under bending stress.

Maximum Crushing Strength: The maximum crushing strength is the maximum stress sustained by a compression parallel-to-grain specimen having a ratio of length to least diameter of less than 11.

Compression Perpendicular to Grain: Strength in compression perpendicular to grain is reported as the stress at the proportional limit because there is no clearly defined ultimate stress for this property.

Shear Strength Parallel to Grain: Shear strength is a measure of the ability to resist internal slipping of one part upon another along the grain. The values listed in the table are averages of the radial and tangential shears.

Tensile Strength Perpendicular to Grain: The tensile strength perpendicular to the grain is a measure of the resistance of wood to forces acting across the grain that tend to split the material. Averages of radial and tangential measurements are listed.

Mechanical Properties of Commercially Important U.S. Grown Woods

Use the first number in each column for GREEN wood; use the second number for DRY wood.	Static Bending: Modulus of Rupture (10^3 psi)		Static Bending: Work to Max Load (in.-lb/in.^{3})		Maximum Crushing Strength (10^3 psi)		Compression Strength Perpendicular to Grain (psi)		Shear Strength Parallel to Grain (psi)		Tensile Strength Perp. to Grain (psi)	
Basswood, American	5.0	8.7	5.3	7.2	2.22	4.73	170	370	600	990	280	350
Cedar, N. white	4.2	6.5	5.7	4.8	1.90	3.96	230	310	620	850	240	240
Cedar, W. red	5.2	7.5	5.0	5.8	2.77	4.56	240	460	770	990	230	220
Douglas Fir, coast[a]	7.7	12.4	7.6	9.9	3.78	7.23	380	800	900	1,130	300	340
Douglas Fir, interior W.	7.7	12.6	7.2	10.6	3.87	7.43	420	760	940	1,290	290	350
Douglas Fir, interior N.	7.4	13.1	8.1	10.5	3.47	6.90	360	770	950	1,400	340	390
Douglas Fir, interior S.	6.8	11.9	8.0	9.0	3.11	6.23	340	740	950	1,510	250	330
Fir, balsam	5.5	9.2	4.7	5.1	2.63	5.28	190	404	662	944	180	180
Hemlock, Eastern	6.4	8.9	6.7	6.8	3.08	5.41	360	650	850	1,060	230	…
Hemlock, Mountain	6.3	11.5	11.0	10.4	2.88	6.44	370	860	930	1,540	330	…
Hemlock, Western	6.6	11.3	6.9	8.3	3.36	7.20	280	550	860	1,290	290	340
Pine, E. white	4.9	9.9	5.2	8.3	2.44	5.66	220	580	680	1,170	250	420
Pine, Virginia	7.3	13.0	10.9	13.7	3.42	6.71	390	910	890	1,350	400	380
Pine, W. white	4.7	9.7	5.0	8.8	2.43	5.04	190	470	680	1,040	260	…
Redwood, old-growth	7.5	10.0	7.4	6.9	4.20	6.15	420	700	800	940	260	240
Redwood, young-growth	5.9	7.9	5.7	5.2	3.11	5.22	270	520	890	1,110	300	250
Spruce, Engelmann	4.7	9.3	5.1	6.4	2.18	4.48	200	410	640	1,200	240	350
Spruce, red	6.0	10.8	6.9	8.4	2.72	5.54	260	550	750	1,290	220	350
Spruce, white	5.0	9.4	6.0	7.7	2.35	5.18	210	430	640	970	220	360

[a] Coast: grows west of the summit of the Cascade Mountains in OR and WA. Interior west: grows in CA and all counties in OR and WA east of but adjacent to the Cascade summit. Interior north: grows in remainder of OR and WA and ID, MT, and WY. Interior south: grows in UT, CO, AZ, and NM.

Results of tests on small, clear, straight-grained specimens. Data for dry specimens are from tests of seasoned material adjusted to a moisture content of 12%.

Source: U.S. Department of Agriculture: *Wood Handbook.*

Effect of Pressure Treatment on Mechanical Properties of Wood.— The strength of wood preserved with creosote, coal-tar, creosote-coal-tar mixtures, creosote-petroleum mixtures, or pentachlorophenol dissolved in petroleum oil is not reduced. However, waterborne salt preservatives contain chemicals such as copper, arsenic, chromium, and ammonia, which have the potential of affecting mechanical properties of treated wood and causing mechanical fasteners to corrode. Preservative salt-retention levels required for marine protection may reduce bending strength by 10 per cent or more.

Density of Wood.— The following formula can be used to find the density of wood in lb/ft^3 as a function of its moisture content.

$$\rho = 62.4\left(\frac{G}{1 + G \times 0.009 \times M}\right)\left(1 + \frac{M}{100}\right)$$

where ρ is the density, G is the specific gravity of wood, and M is the moisture content expressed in per cent.

Weights of American Woods, in Pounds per Cubic Foot (United States Department of Agriculture)

Species	Green	Airdry	Species	Green	Airdry
Alder, red	46	28	Hickory, pecan	62	45
Ash, black	52	34	Hickory, true	63	51
Ash, commercial white	48	41	Honeylocust	61	…
Ash, Oregon	46	38	Larch, western	48	36
Aspen	43	26	Locust, black	58	48
Basswood	42	26	Maple, bigleaf	47	34
Beech	54	45	Maple, black	54	40
Birch	57	44	Maple, red	50	38
Birch, paper	50	38	Maple, silver	45	33
Cedar, Alaska	36	31	Maple, sugar	56	44
Cedar, eastern red	37	33	Oak, red	64	44
Cedar, northern white	28	22	Oak, white	63	47
Cedar, southern white	26	23	Pine, lodgepole	39	29
Cedar, western red	27	23	Pine, northern white	36	25
Cherry, black	45	35	Pine, Norway	42	34
Chestnut	55	30	Pine, ponderosa	45	28
Cottonwood, eastern	49	28	Pines, southern yellow:		
Cottonwood, northern black	46	24	Pine, loblolly	53	36
Cypress, southern	51	32	Pine, longleaf	55	41
Douglas fir, coast region	38	34	Pine, shortleaf	52	36
Douglas fir, Rocky Mt. region	35	30	Pine, sugar	52	25
Elm, American	54	35	Pine, western white	35	27
Elm, rock	53	44	Poplar, yellow	38	28
Elm, slippery	56	37	Redwood	50	28
Fir, balsam	45	25	Spruce, eastern	34	28
Fir, commercial white	46	27	Spruce, Engelmann	39	23
Gum, black	45	35	Spruce, Sitka	33	28
Gum, red	50	34	Sycamore	52	34
Hemlock, eastern	50	28	Tamarack	47	37
Hemlock, western	41	29	Walnut, black	58	38

Machinability of Wood.—The ease of working wood with hand tools generally varies directly with the specific gravity of the wood; the lower the specific gravity, the easier the wood is to cut with a sharp tool. A rough idea of the specific gravity of various woods can be obtained from the preceding table by dividing the weight of wood in lb/ft^3 by 62.355.

A wood species that is easy to cut does not necessarily develop a smooth surface when it is machined. Three major factors, other than specific gravity, influence the smoothness of the surface obtained by machining: interlocked and variable grain, hard deposits in the grain, and reaction wood. Interlocked and variable grain is a characteristic of many tropical and some domestic species; this type of grain structure causes difficulty in planing quarter sawn boards unless careful attention is paid to feed rates, cutting angles, and sharpness of the knives. Hard deposits of calcium carbonate, silica, and other minerals in the grain tend to dull cutting edges quickly, especially in wood that has been dried to the usual in service moisture content. Reaction wood results from growth under some physical stress such as occurs in leaning trunks and crooked branches. Generally, reaction wood occurs as tension wood in hardwoods and as compression wood in softwoods. Tension wood is particularly troublesome, often resulting in fibrous and fuzzy surfaces, especially in woods of lower density. Reaction wood may also be responsible for pinching saw blades, resulting in burning and dulling of teeth.

The following table rates the suitability of various domestic hardwoods for machining. The data for each species represent the percentage of pieces machined that successfully met the listed quality requirement for the processes. For example, 62 per cent of the black walnut pieces planed came out perfect, but only 34 per cent of the pieces run on the shaper achieved good to excellent results.

Machinability and Related Properties of Various Domestic Hardwoods

	Planing	Shaping	Turning	Boring	Mortising	Sanding
	Quality Required					
Type of Wood	Perfect	Good to Excellent	Fair to Excellent	Good to Excellent	Fair to Excellent	Good to Excellent
Alder, red	61	20	88	64	52	…
Ash	75	55	79	94	58	75
Aspen	26	7	65	78	60	…
Basswood	64	10	68	76	51	17
Beech	83	24	90	99	92	49
Birch	63	57	80	97	97	34
Birch, paper	47	22	…	…	…	…
Cherry, black	80	80	88	100	100	…
Chestnut	74	28	87	91	70	64
Cottonwood	21	3	70	70	52	19
Elm, soft	33	13	65	94	75	66
Hackberry	74	10	77	99	72	…
Hickory	76	20	84	100	98	80
Magnolia	65	27	79	71	32	37
Maple, bigleaf	52	56	8	100	80	…
Maple, hard	54	72	82	99	95	38
Maple, soft	41	25	76	80	34	37
Oak, red	91	28	84	99	95	81
Oak, white	87	35	85	95	99	83
Pecan	88	40	89	100	98	…
Sweetgum	51	28	86	92	53	23
Sycamore	22	12	85	98	96	21
Tanoak	80	39	81	100	100	…
Tupelo, black	48	32	75	82	24	21
Tupelo, water	55	52	79	62	33	34
Walnut, black	62	34	91	100	98	…
Willow	52	5	58	71	24	24
Yellow-poplar	70	13	81	87	63	19

The data above represent the percentage of pieces attempted that meet the quality requirement listed.

Nominal and Minimum Sizes of Sawn Lumber

Type of Lumber	Thickness (inches)			Face Widths (inches)		
	Nominal, T_n	Dry	Green	Nominal, W_n	Dry	Green
Boards	1	$\frac{3}{4}$	$\frac{25}{32}$	2 to 4	$W_n - \frac{1}{2}$	$W_n - \frac{7}{16}$
	$1\frac{1}{4}$	1	$1\frac{1}{32}$	5 to 7	$W_n - \frac{1}{2}$	$W_n - \frac{3}{8}$
	$1\frac{1}{2}$	$1\frac{1}{4}$	$1\frac{9}{32}$	8 to 16	$W_n - \frac{3}{4}$	$W_n - \frac{1}{2}$
Dimension Lumber	2	$1\frac{1}{2}$	$1\frac{9}{16}$	2 to 4	$W_n - \frac{1}{2}$	$W_n - \frac{7}{16}$
	$2\frac{1}{2}$	2	$2\frac{1}{16}$	5 to 6	$W_n - \frac{1}{2}$	$W_n - \frac{3}{8}$
	3	$2\frac{1}{2}$	$2\frac{9}{16}$	8 to 16	$W_n - \frac{3}{4}$	$W_n - \frac{1}{2}$
	$3\frac{1}{2}$	3	$3\frac{1}{16}$	…	…	…
	4	$3\frac{1}{2}$	$3\frac{9}{16}$	…	…	…
	$4\frac{1}{2}$	4	$4\frac{1}{16}$	…	…	…
Timbers	5 and up	…	$T_n - \frac{1}{2}$	5 and up	…	$W_n - \frac{1}{2}$

Source: National Forest Products Association: *Design Values for Wood Construction*. Moisture content: dry lumber ≤ 19 percent; green lumber > 19 percent. Dimension lumber refers to lumber 2 to 4 inches thick (nominal) and 2 inches or greater in width. Timbers refers to lumber of approximately square cross-section, 5 × 5 inches or larger, and a width no more than 2 inches greater than the thickness.

Tabulated Properties of Ceramics, Plastics, and Metals

Typical Properties of Ceramics Materials

Material		Density[a] (lb/in.^{3})	Dielectric Strength (V/mil)	Coeff. of Expansion[b] (10^{-6} in./in.-°F)	Flexural Strength (10^3 psi)	Mohs's Hardness[c]	Operating Temperature (°F)	Tensile Strength (10^3 psi)	Compressive Strength (10^3 psi)	Thermal Conductivity[d] (Btu-ft-hr-ft^2-°F)
Machinable Glass Ceramic		0.09	1000	4.1–7.0		48 Ra	1472	…	50	0.85
		0.11	400	6	15	5.5	700	…	40	0.24
		0.10	380	5.2	14	5.0	1100	…	32	0.34
Glass-Mica	Machining-Grades{	0.09–0.10	400	10.5–11.2	12.5–13	90 Rh	750	6	40–45	0.24–0.29
		0.10	380	9.4	11	90 Rh	1100	5	32	0.34
	Molding Grades{	0.13–0.17	300–325	11–11.5	9–10	90 Rh	700–750	6–6.5	33–35	0.29–0.31
		0.14	350	10.3	9	90 Rh	1300	6	30	0.3
Aluminum Silicate		0.10	80	2.5	4.5	1–2	1000	…	12	0.92
		0.08	100	2.9	10	6.0	2100	…	25	0.75
Alumina Silicate		0.08	70	…	…	…	2370	…	…	0.38
Silica Foam		0.03	80	0.3	0.4	NA	2000	…	1.4	0.10
TiO_2 (Titania)		0.14	100	4.61	20	8	1800	7.5	100	…
Lava (Grade A)		0.08	80	1.83	9	6	2000	2.5	40	0.92
Zirconium Phosphate		0.11	NA	0.5	7.5	NA	2800	…	30	0.4 (approx.)
ZrO_2		0.21	…	6.1	102	1300 V	…	…	261	1.69
$ZrO_2 \cdot SiO_2$ (Zircon)		0.11	220	1.94	16	7.5	1825	10	90	…
$2MgO \cdot SiO_2$ (Forsterite)		0.11	240	5.56	20	7.5	1825	10	85	4.58
$MgO \cdot SiO_2$ (Steatite)		0.09–0.10	210–240	3.83–5.44	18–21	7.5	1825	8.5–10	80–90	3.17–3.42
$2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$ (Cordierite)		0.06	60	0.33	3.4	6.5	2000	2.5	18.5	1.00
		0.08	100–172	1.22–1.28	8–12	7–7.5	2000	3.5–3.7	30–40	1.00
		0.09	200	1.33	15	8	2000	4	50	1.83
Al_2O_3	94%	0.13	210	3.33	44	9	2700	20	315	16.00
(Alumina)	96%	0.13–0.14	210	3.5–3.7	48–60	9	2600–2800	25	375	20.3–20.7
	99.5%	0.14	200	3.72	70	9	2700	28	380	21.25
	99.9%	0.14	…	3.75	72	9	2900	…	400	…

[a] Obtain specific gravity by dividing density in lb/in.^{3} by 0.0361; for density in lb/ft^3, multiply lb/in.^{3} by 1728; for g/cm^3, multiply density in lb/in.^{3} by 27.68; for kg/m^3, multiply density in lb/in.^{3} by 27,679.9.

[b] To convert coefficient of expansion to 10^{-6} in./in.-°C, multiply table value by 1.8.

[c] Mohs's Hardness scale is used unless otherwise indicated as follows: Ra and Rh for Rockwell A and H scales, respectively; V for Vickers hardness.

[d] To convert conductivity from Btu-ft/hr-ft^2-°F to cal-cm/sec-cm^2-°C, divide by 241.9.

Typical Properties of Plastics Materials

Material	Density[a] (lb/in³)	Specific Gravity	Dielectric Strength (V/mil)	Coeff. of Expansion[b] (10^{-6} in/in-°F)	Tensile Modulus (10^5 psi)	Izod Impact (ft-lb/in of notch)	Flexural Modulus (ksi at 73°F)	% Elongation	Hardness[c]	Max. Operating Temp. (°F)
ABS, Extrusion Grade	0.038	1.05	…	53.0	275	7	300	…	105 Rr	200
ABS, High Impact	0.037	1.03	…	…	200	…	330	…	105 Rr	…
Acetal, 20% Glass	0.056	1.55	…	…	1000	0.9	715	…	94 Rm	…
Acetal, Copolymer	0.051	1.41	380	47.0	437	2	400	13	94 Rm	…
Acetyl, Homopolymer	0.051	1.41	…	58.0	310	…	320	…	94 Rm	200
Acrylic	0.043	1.19	500	35.0	400	0.5	400	2.7	94 Rm	180
Azdel	0.043	1.19	500	15.0	750	14	800	2.1	94 Rm	311
CPVC	0.056	1.55	…	34.0	400	3	400	4	…	212
Fiber Glass Sheet	0.067	1.87	…	11.1	…	8	1	…	101 Rm	260
Nylon 6, 30% Glass	0.050	1.39	…	…	1350	2.8	1400	…	119 Rr	…
Nylon 6, Cast	0.042	1.16	295	45.0	380	1.4	450	20	100 Rr	210
Nylon 6⁄6, Cast	0.047	1.30	…	…	…	…	…	…	…	…
Nylon 6⁄6, Extruded	0.041	1.14	600	45.0	390	1	…	240	118 Rr	230
Nylon 60L, Cast	0.042	1.16	…	…	…	2.2	…	…	…	…
PET, unfilled	0.049	1.36	1300	39.0	500	0.5	400	70	…	230
PTFE (Teflon)	0.079	2.19	480	50.0	225	3	80	350	…	…
PVC	0.050	1.39	500	29.5	550	0.8	400	31–40	110 Rr	170
PVDF	0.064	1.77	260	60.0	320	3	200	80	100 Rr	180
Phenolics	0.050	1.38	…	11.1	…	2.4	1000	…	100 Rm	248
Polycarbonate	0.043	1.19	380	37.5	345	14	340	110	74 Rm	290
Polyetherimide	0.046	1.27	480	…	430	1.1	480	…	…	…
Polyethylene, HD	0.035	0.97	475	20.0	156	6	160	900	…	180
Polyethylene, UHMW	0.034	0.94	710	19.0	110	No Break	130	450	64 Rr	176
Polymethylpentene	0.030	0.83	…	…	220	2.5	…	…	…	…
Polymid, unfilled	0.051	1.41	560	…	300	1.5	…	…	…	…
Polyphenylene Sulfide	0.047	1.30	380	…	…	0.5	550	…	…	…
Polypropylene	0.033	0.91	600	96.0	155	0.75	200	120	92 Rr	150
Polysulfone	0.045	1.25	425	31.0	360	1.2	390	50	120 Rr	325
Polyurethane	0.038	1.05	…	…	…	…	…	465–520	…	…

[a] To obtain specific gravity, divide density in lb/in³ by 0.0361; for density in lb/ft³, multiply lb/in³ by 1728; for g/cm³, multiply density in lb/in³ by 27.68; for kg/m³, multiply density in lb/in³ by 27,679.9.

[b] To convert coefficient of expansion to 10^{-6} in/in-°C, multiply table value by 1.8.

[c] Hardness value scales are as follows: Rm for Rockwell M scale; Rr for Rockwell R scale.

Mechanical Properties of Various Investment Casting Alloys

Alloy Designation	Material Condition	Tensile Strength (10^3 psi)	0.2% Yield Strength[a] (10^3 psi)	% Elonga-tion	Hardness
Aluminum					
356	As Cast	32–40	22–30	3–7	…
A356	As Cast	38–40	28–36	3–10	…
A357	As Cast	33–50	27–40	3–9	…
355, C355	As Cast	35–50	28–39	1–8	…
D712 (40E)	As Cast	34–40	25–32	4–8	…
A354	As Cast	47–55	36–45	2–5	…
RR-350	As Cast	32–45	24–38	1.5–5	…
Precedent 71	As Cast	35–55	25–45	2–5	…
KO-1	As Cast	56–60	48–55	3–5	…
Copper-Base Alloys[a]					
Al Bronze C (954)	As Cast	75–85	30–40	10–20	80–85 Rb
	Heat-Treated	90–105	45–55	6–10	91–96 Rb
Al Bronze D (955)	As Cast	90–100	40–50	6–10	91–96 Rb
	Heat-Treated	110–120	60–70	5–8	93–98 Rb
Manganese Bronze, A	…	65–75	25–40	16–24	60–65 Rb
Manganese Bronze, C	…	110–120	60–70	8–16	95–100 Rb
Silicon Bronze	…	45	18	20	…
Tin Bronze	…	40–50	18–30	20–35	40–50 Rb
Lead. Yellow Brass (854)	…	30–50	11–20	15–25	…
Red Brass	…	30–40	14–25	20–30	30–35 Rb
Silicon Brass	…	70	32	24	…
Pure Copper	…	20–30	…	4–50	35–42 Rb
Beryllium Cu 10C (820)	As Cast	45–50	40–45	15–20	50–55 Rb
	Hardened	90–100	90–130	3–8	90–95 Rb
Beryllium Cu 165C (824)	…	70–155	40–140	1–15	60 Rb–38 Rc
Beryllium Cu 20C (825)	As Cast	70–80	50–55	18–23	75–80 Rb
	Hardened	110–160	…	1–4	25–44 Rc
Beryllium Cu 275C (828)	As Cast	80–90	…	15–20	80–85 Rb
Chrome Copper	…	33–50	20–40	20–30	70–78 Rb
Carbon and Low-Alloy Steels and Iron					
IC 1010	Annealed	50–60	30–35	30–35	50–55 Rb
IC 1020	Annealed	60–70	40–45	25–40	80 Rb
IC 1030	Annealed	65–75	45–50	20–30	75 Rb
	Hardened	85–150	60–150	0–15	20–50 Rc
IC 1035	Annealed	70–80	45–55	20–30	80 Rb
	Hardened	90–150	85–150	0–15	25–52 Rc
IC 1045	Annealed	80–90	50–60	20–25	100 Rb
	Hardened	100–180	90–180	0–10	25–57 Rc
IC 1050	Annealed	90–110	50–65	20–25	100 Rb
	Hardened	125–180	100–180	0–10	30–60 Rc
IC 1060	Annealed	100–120	55–70	5–10	25 Rc
	Hardened	120–200	100–180	0–3	30–60 Rc
IC 1090	Annealed	110–150	70–80	12–20	30 Rc
	Hardened	130–180	130–180	0–3	37–50 Rc
IC 2345	Hardened	130–200	110–180	5–10	30–58 Rc
IC 4130	Hardened	130–170	100–130	5–20	23–49 Rc
IC 4140	Hardened	130–200	100–155	5–20	29–57 Rc
IC 4150	Hardened	140–200	120–180	5–10	25–58 Rc
IC 4330	Hardened	130–190	100–175	5–20	25–48 Rc
IC 4340	Hardened	130–200	100–180	5–20	20–55 Rc
IC 4620	Hardened	110–150	90–130	10–20	20–32 Rc
IC 6150, IC 8740	Hardened	140–200	120–180	5–10	30–60 Rc
IC 8620	Hardened	100–130	80–110	10–20	20–45 Rc
IC 8630	Hardened	120–170	100–130	7–20	25–50 Rc
IC 8640	Hardened	130–200	100–180	5–20	30–60 Rc

Mechanical Properties of Various Investment Casting Alloys *(Continued)*

Alloy Designation	Material Condition	Tensile Strength (10^3 psi)	0.2% Yield Strength[a] (10^3 psi)	% Elonga-tion	Hardness
Carbon and Low-Alloy Steels and Iron *(Continued)*					
IC 8665	Hardened	170–220	140–200	0–10	…
IC 8730	Hardened	120–170	110–150	7–20	…
IC 52100	Hardened	180–230	140–180	1–7	30–65 Rc
IC 1722AS	Hardened	130–170	100–140	6–12	25–48 Rc
1.2% Si Iron	…	50–60	37–43	30–35	55 Rb
Ductile Iron, Ferritic	Annealed	60–80	40–50	18–24	143–200 Bhn
Ductile Iron, Pearlitic	Normalized	100–120	70–80	3–10	243–303 Bhn
Hardenable Stainless Steel					
CA-15	Hardened	95–200	75–160	5–12	94 Rb–45 Rc
IC 416	Hardened	95–200	75–160	3–8	94 Rb–45 Rc
CA-40	Hardened	200–225	130–210	0–5	30–52 Rc
IC 431	Hardened	110–160	75–105	5–20	20–40 Rc
IC 17–4	Hardened	150–190	140–160	6–20	34–44 Rc
Am-355	Hardened	200–220	150–165	6–12	…
IC 15–5	Hardened	135–170	110–145	5–15	26–38 Rc
CD-4M Cu	Annealed	100–115	75–85	20–30	94–100 Rb
	Hardened	135–145	100–120	10–25	28–32 Rc
Austenitic Stainless Steels					
CF-3, CF-3M, CF-8, CF-8M, IC 316F	Annealed	70–85	40–50	35–50	90 Rb (max)
CF-8C	Annealed	70–85	32–36	30–40	90 Rb (max)
CF-16F	Annealed	65–75	30–35	35–45	90 Rb (max)
CF-20	Annealed	65–75	30–45	35–60	90 Rb (max)
CH-20	Annealed	70–80	30–40	30–45	90 Rb (max)
CN-7M	Annealed	65–75	25–35	35–45	90 Rb (max)
IC 321, CK-20	Annealed	65–75	30–40	35–45	90 Rb (max)
Nickel-Base Alloys					
Alloy B	Annealed	75–85	50–60	8–12	90–100 Rb
Alloy C	As Cast	80–95	45–55	8–12	90–100 Rb
	Annealed	75–95	45–55	8–12	90 Rb–25 Rc
Alloy X[b]	AC to 24°C	63–70	41–45	10–15	85–96 Rb
	AC to 816°C	35–45	…	12–20	…
Invar (Fe–Ni alloy)	As Cast	50–60	25–30	30–40	50–60 Rb
In 600 (Inconel)	As Cast	65–75	35–40	10–20	80–90 Rb
In 625 (Inconel)	Annealed	80–100	40–55	15–30	10–20 Rc
Monel 410	As Cast	65–75	32–38	25–35	65–75 Rb
S Monel	Annealed	100–110	55–65	5–10	20–28 Rc
	Hardened	120–140	85–100	0	32–38 Rc
RH Monel	As Cast	100–110	60–80	10–20	20–30 Rc
Monel E	As Cast	65–80	33–40	25–35	67–78 Rb
M-35 Monel	As Cast	65–80	25–35	25–40	65–85 Rb
Cobalt-Base Alloys					
Cobalt 21	As Cast	95–130	65–95	8–20	24–32 Rc
Cobalt 25	As Cast	90–120	60–75	15–25	20–25 Rc
Cobalt 31	As Cast	105–130	75–90	6–10	20–30 Rc
Cobalt 36	As Cast	90–105	60–70	15–20	30–36 Rc
F75	As Cast	95–110	70–80	8–15	25–34 Rc
N-155	Sol. Anneal	90–100	50–60	15–30	90–100 Rb

[a] For copper alloys, yield strength is determined by 0.5% extension under load or 0.2% offset method. A number in parentheses following a copper alloy indicates the UNS designation of that alloy (for example, Al Bronze C (954) identifies the alloy as UNS C95400).

[b] AC = air cooled to temperature indicated.

Source: Investment Casting Institute. Mechanical properties are average values of separately cast test bars, and are for reference only. Items marked … indicates data are not available. Alloys identified by IC followed by an SAE designation number (IC 1010 steel, for example) are generally similar to the SAE material although properties and chemical composition may be different.

Typical Properties of Compressed and Sintered Powdered Metal Alloys

Alloy Number[a] and Nominal Composition (%)		Density (g/cc)	Hardness	Strength (10^3 psi)			% Elongation
				Transverse Rupture	Ultimate Tensile	Yield	
Copper Base							
…	100Cu	7.7–7.9	81–82 Rh	54–68	24–34	…	10–26
CZP-3002	70Cu, 1.5Pb, Bal. Zn	8	75 Rh	…	33.9	…	24
CNZ-1818	63Cu, 17.5Ni, Bal. Zn	7.9	90 Rh	73	34	20	11
CTG-1004	10Sn, 4.4C, Bal. Cu	7	67 Rh	20	9.4	6.5	6
CTG-1001	10Sn, 1C, Bal. Cu	6.5	45 Rh	25.8	15.1	9.6	9.7
Iron Base (Balance of composition, Fe)							
FC-2015	23.5Cu, 1.5C	6.5	65 Rb	80	52.4	48.5	0
FC-0800	8Cu, 0.4C	6.3–6.8	39–55 Rb	75–100	38–54	32–47	1 or less
FX-2008	20Cu, 1C	7.3	93 Rb	164.2	72.3	57.7	2
FN-0408	4Ni, 1–2Cu, 0.75C	6.3–7	64–84 Rb	70–107	37–63	30–47	1–1.6
F-0000	100Fe	6.5	26 Rf	37.7	15.7	11	5.7
FN-0005	0.45C, 0.50 MnS	6.4–6.8	66–78 Rf	44–61	…	…	…
F-0000	0.02C, 0.45P	6.6–7.2	35–50 Rb	90–125	…	29–38	3.9–5.5
F-0008	0.6–0.9C	6.2–7	50–70 Rb	61–100	35–57	30–40	<0.5 to 1
FC-0508	0.6–0.9C, 4–6Cu	5.9–6.8	60–80 Rb	100–145	58–82	50–70	<0.5 to 1
FN-0405	4Ni, 0.5C	6.6–7.0	73–82 Rb	90–100	47–50	38–40	<1
FN-0208	2Ni, 0.8C	6.6–7.0	50–70 Rb	70–108	47–58	35–51	<1
FN-0205	2Ni, 0.5C	6.6–7.0	51–61 Rb	72–93	35–45	27–31	2.0–2.5
FN-0200	2Ni, 0.25C	6.6	29 Rb	57.5	25.8	19.0	1.3
FC-0208	2Cu, 0.75C	6.5–6.7	68–72 Rb	95–107	56–61	51–54	up to 1
FC-2008	20Cu, 1C	6.2	45 Rb	79.5	47.8	40.0	1.3
…	4Ni, 0.6C, 1.6Cu, 0.55Mo	7.0	92 Rb	190.0	100.0	65.0	2.5
FL-4605	1.8Ni, 0.6C, 1.6Cu, 0.55Mo	7.0	87 Rb	170.0	80.0	55.0	2.5
FL-4605	1.8Ni, 0.6C, 0.55Mo	7.0	80 Rb	150.0	…	…	…
SS-316L	17Cr, 13Ni, 2.2Mo, 0.9Si	6.5	65 Rb	94.0	45.0	30.0	6.0
…	17Cr, 13Ni, 2.2Mo, 0.9Si, 15–20Cu	7.3	66 Rb	108.6	59.2	49.7	4.3
SS-410	13Cr, 0.8Si, 0.8Mn	6.2	15 Rc	85.0	66.7	56.9	0
FL-4608	2Cu, 3.8Ni, 0.9C, 0.75Mo	6.8	24 Rc	107.3	55.8	46.5	1.5
SS-303N1	18Cr, 11Ni, 1Mn	6.4	62 Rb	86.0	39.0	32.0	0.5
SS-304N1	19Cr, 10Ni, 1Mn	6.4	61 Rb	112.0	43.0	38.0	0.5
Tungsten Base							
90W, 6Ni, 4Cu		17.0	24 Rc	…	110	80	6
90W, 7Ni, 3Cu		17.0	25 Rc	…	120	88	10
92.5W, 5.25Ni, 2.25Cu		17.5	26 Rc	…	114	84	7
92.5W, Bal. Ni, Fe, and Mo		17.6	30 Rc	…	120	90	4
93W, Bal. Ni, Fe, and Mo		17.7	32 Rc	…	125	95	4
95W, 3.5Ni, 1.5Cu		18.0	27 Rc	…	110	85	7
95W, 3.5Ni, 1.5Fe		18.0	27 Rc	…	120	90	7
97W, 2.1Ni, 0.9Fe		18.5	28 Rc	…	123	85	5

[a] Copper- and iron-base alloy designations are Metal Powder Industries Federation (MPIF) alloy numbers.

Typical Elastic Properties of Materials

Material	Modulus of Elasticity (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio
Aluminum, var. alloys	9.9–10.3	3.7–3.9	9.9–10.2	0.330–0.334
Aluminum, 6061-T6	10.2	3.8	…	0.35
Aluminum, 2024-T4	10.6	4.0	…	0.32
Beryllium copper	18	7	…	0.29
Brass, 70–30	15.9	6	15.7	0.331
Brass, cast	14.5	5.3	16.8	0.357
Bronze	14.9	6.5	…	0.14
Copper	15.6	5.8	17.9	0.355
Glass	6.7	2.7	…	0.24
Glass ceramic (machinable)	9.7	3.7	…	0.29
Inconel	31	11	…	0.27–0.38
Iron, cast	13.5–21.0	5.2–8.2	8.4–15.5	0.221–0.299
Iron, ductile	23.8–25.2	9.1–9.6	…	0.26–0.31
Iron, grey cast	14.5	6	…	0.211
Iron, malleable	23.6	9.3	17.2	0.271
Lead	5.3	1.9	…	0.43
Magnesium	6.5	2.4	…	0.35
Magnesium alloy	6.3	2.5	4.8	0.281
Molybdenum	48	17	…	0.307
Monel metal	25	9.5	22.5	0.315
Nickel silver	18.5	7	…	0.322
Nickel steel	30	11.5	…	0.291
Phosphor bronze	13.8	5.1	16.3	0.359
Stainless steel 18–8	27.6	10.6	23.6	0.305
Steel, cast	28.5	11.3	20.2	0.265
Steel, cold-rolled	29.5	11.5	23.1	0.287
Steel, all others	28.6–30.0	11.0–11.9	22.6–24.0	0.283–0.292
Titanium (99.0 Ti)	15–16	6.5	…	0.24
Titanium (Ti-8Al-1Mo-1V)	18	6.8	…	0.32
Zinc, cast alloys	10.9–12.4	…	…	0.33
Zinc, wrought alloys	6.2–14	…	…	0.33
Z-nickel	30	11	…	0.36

Data represent typical values, but material properties may vary widely, depending on exact composition, material condition, and processing. Symbol … indicates no data available.

Minimum Tensile Strength of Spring Wire by Diameter

Wire Dia. (in.)	Wire Type						
	Music Wire	Hard-Drawn MB	Oil Temp. MB	Stainless Steel 18-8	Cr–V Alloy	Phosphor Bronze	Chrome Silicon
	Minimum Tensile Strength (10^3 psi)						
0.004	439	…	…	325	…	140	…
0.008	399	…	…	325	…	140	…
0.012	377	…	…	316	…	…	…
0.020	350	283	288	300	…	…	…
0.028	333	271	281	284	…	…	…
0.032	327	265	275	278	281	…	300
0.035	322	261	268	274	276	…	298
0.041	314	255	261	270	270	135	298
0.047	307	248	254	262	263	…	292
0.054	301	243	248	258	257	…	292
0.063	293	237	242	251	251	130	290
0.072	287	232	236	245	245	…	288
0.080	282	227	230	240	240	…	285
0.092	275	220	225	233	235	…	280
0.105	269	216	220	227	229	125	275
0.120	263	210	215	221	222	…	275
0.135	258	206	210	213	219	…	270
0.148	253	203	205	207	215	…	268
0.162	249	200	200	200	212	…	162
0.177	245	195	195	195	210	…	260
0.192	241	192	190	189	206	…	260
0.207	238	190	185	185	204	…	260
0.225	225	186	183	180	200	120	255
0.250	220	182	180	174	196	…	250
0.312	…	174	178	160	189	110	245
0.375	…	167	175	…	187	…	240
0.437	…	165	170	…	186	…	235
0.500	…	156	165	…	185	100	230

For allowable working stresses and recommended design stresses in bending, related to severity of service, refer to Fig. 1 through Fig. 10 on pages 291 through 294, and for endurance limits for compression springs made from these materials refer to Fig. 11 on page 296 in the section on spring stresses.

Pressure and Flow of Water

Water Pressure.— Water is composed of two elements, hydrogen and oxygen, in the ratio of two volumes of hydrogen to one of oxygen. In the common system of measure, water boils under atmospheric pressure at 212 degrees F and freezes at 32 degrees F. Water's greatest density is 62.425 pounds per cubic foot, at 39.1 degrees F. In metric (SI) measure, water boils under atmospheric pressure at 100°C (Celsius) and freezes at 0°C. Its density is equal to 1 kilogram per liter, where 1 liter is 1 cubic decimeter. Also in metric SI, pressure is given in pascals (Pa) or the equivalent newtons per square meter. See page 2523 for additional information on the metric (SI) system of units.

For higher temperatures, the pressure slightly decreases in the proportion indicated by the table *Weight of Water per Cubic Foot at Different Temperatures*. The pressure per square inch is equal in all directions, downwards, upwards, and sideways. Water can be compressed only to a very slight degree, the compressibility being so slight that even at the depth of a mile, a cubic foot of water weighs only about one-half pound more than at the surface.

Pressure in Pounds per Square Inch for Different Heads of Water

Head, ft	0	1	2	3	4	5	6	7	8	9
0	…	0.43	0.87	1.30	1.73	2.16	2.60	3.03	3.46	3.90
10	4.33	4.76	5.20	5.63	6.06	6.49	6.93	7.36	7.79	8.23
20	8.66	9.09	9.53	9.96	10.39	10.82	11.26	11.69	12.12	12.56
30	12.99	13.42	13.86	14.29	14.72	15.15	15.59	16.02	16.45	16.89
40	17.32	17.75	18.19	18.62	19.05	19.48	19.92	20.35	20.78	21.22
50	21.65	22.08	22.52	22.95	23.38	23.81	24.25	24.68	25.11	25.55
60	25.98	26.41	26.85	27.28	27.71	28.14	28.58	29.01	29.44	29.88
70	30.31	30.74	31.18	31.61	32.04	32.47	32.91	33.34	33.77	34.21
80	34.64	35.07	35.51	35.94	36.37	36.80	37.24	37.67	38.10	38.54
90	38.97	39.40	39.84	40.27	40.70	41.13	41.57	42.00	42.43	42.87

Heads of Water in Feet Corresponding to Certain Pressures in Pounds per Square Inch

Pressure, lb/in.^{2}	0	1	2	3	4	5	6	7	8	9
0	…	2.3	4.6	6.9	9.2	11.5	13.9	16.2	18.5	20.8
10	23.1	25.4	27.7	30.0	32.3	34.6	36.9	39.3	41.6	43.9
20	46.2	48.5	50.8	53.1	55.4	57.7	60.0	62.4	64.7	67.0
30	69.3	71.6	73.9	76.2	78.5	80.8	83.1	85.4	87.8	90.1
40	92.4	94.7	97.0	99.3	101.6	103.9	106.2	108.5	110.8	113.2
50	115.5	117.8	120.1	122.4	124.7	127.0	129.3	131.6	133.9	136.3
60	138.6	140.9	143.2	145.5	147.8	150.1	152.4	154.7	157.0	159.3
70	161.7	164.0	166.3	168.6	170.9	173.2	175.5	177.8	180.1	182.4
80	184.8	187.1	189.4	191.7	194.0	196.3	198.6	200.9	203.2	205.5
90	207.9	210.2	212.5	214.8	217.1	219.4	221.7	224.0	226.3	228.6

Comparison of Different Units of Pressure

lb/in.^{2}	oz/in.^{2}	Water[a] Inches of	Water[a] Feet of	Mercury[b] Inches of	Mercury[b] mm of	Pascal (N/m^2)
1.0	16.0	27.7066	2.3089	2.0360	51.7149	6,894.757
0.063	1.0	1.732	0.144	0.127	3.232	430.922
0.036	0.578	1.0	0.083	0.074	1.867	248.640
0.433	6.930	12.000	1.0	0.882	22.398	2,983.680
0.491	7.858	13.608	1.134	1.0	25.400	3,383.493
0.019	0.309	0.536	0.045	0.039	1.0	133.271
0.000145	0.0023	0.00402	0.00033	0.00030	0.00750	1.0
2	32	55.413	4.618	4.072	103.430	13,790
3	48	83.120	6.927	6.108	155.145	20,684
4	64	110.826	9.236	8.144	206.860	27,579
5	80	138.533	11.544	10.180	258.575	34,474
6	96	166.240	13.853	12.216	310.289	41,369
7	112	193.946	16.162	14.252	362.004	48,263
8	128	221.653	18.471	16.288	413.719	55,158
9	144	249.359	20.780	18.324	465.434	62,053
10	160	277.066	23.089	20.360	517.149	68,948
11	176	304.773	25.398	22.396	568.864	75,842
12	192	332.479	27.707	24.432	620.579	82,737
13	208	360.186	30.015	26.468	672.294	89,632
14	224	387.892	32.324	28.504	724.009	96,527
15	240	415.599	34.633	30.540	775.724	103,421
16	256	443.306	36.942	32.576	827.438	110,316
17	272	471.012	39.251	34.612	879.153	117,211
18	288	498.719	41.560	36.648	930.868	124,106
19	304	526.425	43.869	38.684	982.583	131,000
20	320	554.132	46.178	40.720	1034.298	137,895
21	336	581.839	48.487	42.756	1086.013	144,790
22	352	609.545	50.795	44.792	1137.728	151,685
23	368	637.252	53.104	46.828	1189.443	158,579
24	384	664.958	55.413	48.864	1241.158	165,474
25	400	692.665	57.722	50.901	1292.873	172,369

[a] Measured at 60°F
[b] Measured at 32°F (0°C).
To convert pascal to bars, divide by 100,000.

Volumes of Water at Different Temperatures

Degrees F	Volume	Degrees F	Volume	Degrees F	Volume	Degrees F	Volume
39.1	1.00000	86	1.00425	131	1.01423	176	1.02872
50	1.00025	95	1.00586	140	1.01678	185	1.03213
59	1.00083	104	1.00767	149	1.01951	194	1.03570
68	1.00171	113	1.00967	158	1.02241	203	1.03943
77	1.00286	122	1.01186	167	1.02548	212	1.04332

Flow of Water in Pipes.—The quantity of water that will flow through a pipe depends primarily on the head but also on the diameter of the pipe, the character of the interior surface, and the number and shape of the bends. The head may be either the distance between the levels of the surface of water in a reservoir and the point of discharge, or it may be caused by mechanically applied pressure, as by pumping, when the head is calculated as the vertical distance corresponding to the pressure.

One pound per square inch is equal to 2.309 feet head, and a 1-foot head is equal to a pressure of 0.433 pound per square inch.

Weight of Water per Cubic Foot at Different Temperatures

Temp. (°F)	Wt. per Cu Ft (lb/ft³)	Temp. (°F)	Wt. per Cu Ft (lb/ft³)	Temp. (°F)	Wt. per Cu Ft (lb/ft³)	Temp. (°F)	Wt. per Cu Ft (lb/ft³)	Temp. (°F)	Wt. per Cu Ft (lb/ft³)	Temp. (°F)	Wt. per Cu Ft (lb/ft³)
32	62.42	130	61.56	220	59.63	320	56.66	420	52.6	520	47.6
40	62.42	140	61.37	230	59.37	330	56.30	430	52.2	530	47.0
50	62.41	150	61.18	240	59.11	340	55.94	440	51.7	540	46.3
60	62.37	160	60.98	250	58.83	350	55.57	450	51.2	550	45.6
70	62.31	170	60.77	260	58.55	360	55.18	460	50.7	560	44.9
80	62.23	180	60.55	270	58.26	370	54.78	470	50.2	570	44.1
90	62.13	190	60.32	280	57.96	380	54.36	480	49.7	580	43.3
100	62.02	200	60.12	290	57.65	390	53.94	490	49.2	590	42.6
110	61.89	210	59.88	300	57.33	400	53.50	500	48.7	600	41.8
120	61.74	212	59.83	310	57.00	410	53.00	510	48.1	…	…

Table of Horsepower due to Certain Head of Water

Head in Feet	Horse-power	Head in Feet	Horse-power	Head in Feet	Horse-power	Head in Feet	Horse-power	Head in Feet	Horse-power
1	0.0016	170	0.274	340	0.547	520	0.837	1250	2.012
10	0.0161	180	0.290	350	0.563	540	0.869	1300	2.093
20	0.0322	190	0.306	360	0.580	560	0.901	1350	2.173
30	0.0483	200	0.322	370	0.596	580	0.934	1400	2.254
40	0.0644	210	0.338	380	0.612	600	0.966	1450	2.334
50	0.0805	220	0.354	390	0.628	650	1.046	1500	2.415
60	0.0966	230	0.370	400	0.644	700	1.127	1550	2.495
70	0.1127	240	0.386	410	0.660	750	1.207	1600	2.576
80	0.1288	250	0.402	420	0.676	800	1.288	1650	2.656
90	0.1449	260	0.418	430	0.692	850	1.368	1700	2.737
100	0.1610	270	0.435	440	0.708	900	1.449	1750	2.818
110	0.1771	280	0.451	450	0.724	950	1.529	1800	2.898
120	0.1932	290	0.467	460	0.740	1000	1.610	1850	2.978
130	0.2093	300	0.483	470	0.757	1050	1.690	1900	3.059
140	0.2254	310	0.499	480	0.773	1100	1.771	1950	3.139
150	0.2415	320	0.515	490	0.789	1150	1.851	2000	3.220
160	0.2576	330	0.531	500	0.805	1200	1.932	2100	3.381

The table gives the horsepower of 1 cubic foot of water per minute, and is based on an efficiency of 85 per cent.

All formulas for finding the amount of water that will flow through a pipe in a given time are approximate. The formula that follows will give results within 5 or 10 per cent of actual flows, if applied to pipe lines carefully laid and in fair condition.

$$V = C\sqrt{\frac{hD}{L + 54D}}$$

where V = approximate mean velocity in feet per second

C = coefficient from the accompanying table

D = diameter of pipe in feet

h = total head in feet

L = total length of pipe line in feet

Values of Coefficient *C*

Dia. of Pipe			Dia. of Pipe			Dia. of Pipe		
Feet	Inches	*C*	Feet	Inches	*C*	Feet	Inches	*C*
0.1	1.2	23	0.8	9.6	46	3.5	42	64
0.2	2.4	30	0.9	10.8	47	4.0	48	66
0.3	3.6	34	1.0	12.0	48	5.0	60	68
0.4	4.8	37	1.5	18.0	53	6.0	72	70
0.5	6.0	39	2.0	24.0	57	7.0	84	72
0.6	7.2	42	2.5	30.0	60	8.0	96	74
0.7	8.4	44	3.0	36.0	62	10.0	120	77

Example: A pipe line, 1 mile long, 12 inches in diameter, discharges water under a head of 100 feet. Find the velocity and quantity of discharge.

From the table, the coefficient *C* is found to be 48 for a pipe 1 foot in diameter, hence:

$$V = 48\sqrt{\frac{100 \times 1}{5280 + 54 \times 1}} = 6.57 \text{ feet per second}$$

To find the discharge in cubic feet per second, multiply the velocity found by the area of cross-section of the pipe in square feet:

$$6.57 \times 0.7854 = 5.16 \text{ cubic feet per second}$$

The loss of head due to a bend in the pipe is most frequently given as the equivalent length of straight pipe, which would cause the same loss in head as the bend. Experiments show that a right-angle bend should have a radius of about three times the diameter of the pipe. Assuming this curvature, then, if d is the diameter of the pipe in inches and L is the length of straight pipe in feet that causes the same loss of head as the bend in the pipe, the following formula gives the equivalent length of straight pipe that should be added to simulate a right-angle bend:

$$L = 4d \div 3$$

Thus, the loss of head due to a right-angle bend in a 6-inch pipe would be equal to that in 8 feet of straight pipe. Experiments undertaken to determine the losses due to valves in pipe lines indicate that a fully open gate valve in a pipe causes a loss of head corresponding to the loss in a length of pipe equal to six diameters.

Flow of Water Through Nozzles in Cubic Feet per Second

Head in Feet, at Nozzle	Pressure, lb/in.^{2}	Theoretical Velocity, ft/s	Diameter of Nozzle, Inches							
			1	1.5	2	2.5	3	3.5	4	4.5
5	2.17	17.93	0.10	0.22	0.39	0.61	0.88	1.20	1.56	1.98
10	4.33	25.36	0.14	0.31	0.55	0.86	1.24	1.69	2.21	2.80
20	8.66	35.87	0.20	0.44	0.78	1.22	1.76	2.40	3.13	3.96
30	12.99	43.93	0.24	0.54	0.96	1.50	2.16	2.93	3.83	4.85
40	17.32	50.72	0.28	0.62	1.11	1.73	2.49	3.39	4.43	5.60
50	21.65	56.71	0.31	0.70	1.24	1.93	2.78	3.79	4.95	6.26
60	25.99	62.12	0.34	0.76	1.36	2.12	3.05	4.15	5.42	6.86
70	30.32	67.10	0.37	0.82	1.46	2.29	3.29	4.48	5.86	7.41
80	34.65	71.73	0.39	0.88	1.56	2.45	3.52	4.79	6.26	7.92
90	38.98	76.08	0.41	0.93	1.66	2.59	3.73	5.08	6.64	8.40
100	43.31	80.20	0.44	0.98	1.75	2.73	3.94	5.36	7.00	8.86
120	51.97	87.85	0.48	1.08	1.92	2.99	4.31	5.87	7.67	9.70
140	60.63	94.89	0.52	1.16	2.07	3.23	4.66	6.34	8.28	10.48
160	69.29	101.45	0.55	1.24	2.21	3.46	4.98	6.78	8.85	11.20
180	77.96	107.60	0.59	1.32	2.35	3.67	5.28	7.19	9.39	11.88
200	86.62	113.42	0.62	1.39	2.47	3.87	5.57	7.58	9.90	12.53
250	108.27	126.81	0.69	1.56	2.77	4.32	6.22	8.47	11.07	14.01
300	129.93	138.91	0.76	1.70	3.03	4.74	6.82	9.28	12.12	15.34
350	151.58	150.04	0.82	1.84	3.27	5.11	7.37	10.02	13.09	16.57
400	173.24	160.40	0.87	1.97	3.50	5.47	7.87	10.72	14.00	17.72
450	194.89	170.13	0.93	2.09	3.71	5.80	8.35	11.37	14.85	18.79
500	216.54	179.33	0.98	2.20	3.91	6.11	8.80	11.98	15.65	19.81

Head in Feet, at Nozzle	Pressure, lb/in.^{2}	Theoretical Velocity, ft/s	Diameter of Nozzle, Inches							
			5	6	7	8	9	10	11	12
5	2.17	17.93	2.45	3.52	4.79	6.3	7.9	9.8	11.8	14.1
10	4.33	25.36	3.46	4.98	6.78	8.9	11.2	13.8	16.7	19.9
20	8.66	35.87	4.89	7.04	9.59	12.5	15.8	19.6	23.7	28.2
30	12.99	43.93	5.99	8.63	11.74	15.3	19.4	24.0	29.0	34.5
40	17.32	50.72	6.92	9.96	13.56	17.7	22.4	27.7	33.5	39.8
50	21.65	56.71	7.73	11.13	15.16	19.8	25.1	30.9	37.4	44.5
60	25.99	62.12	8.47	12.20	16.60	21.7	27.4	33.9	41.0	48.8
70	30.32	67.10	9.15	13.18	17.93	23.4	29.6	36.6	44.3	52.7
80	34.65	71.73	9.78	14.08	19.17	25.0	31.7	39.1	47.3	56.3
90	38.98	76.08	10.37	14.94	20.33	26.6	33.6	41.5	50.2	59.8
100	43.31	80.20	10.94	15.75	21.43	28.0	35.4	43.7	52.9	63.0
120	51.97	87.85	11.98	17.25	23.48	30.7	38.8	47.9	58.0	69.0
140	60.63	94.89	12.94	18.63	25.36	33.1	41.9	51.8	62.6	74.5
160	69.29	101.45	13.83	19.92	27.11	35.4	44.8	55.3	66.9	79.7
180	77.96	107.60	14.67	21.13	28.76	37.6	47.5	58.7	71.0	84.5
200	86.62	113.42	15.47	22.27	30.31	39.6	50.1	61.9	74.9	89.1
250	108.27	126.81	17.29	24.90	33.89	44.3	56.0	69.2	83.7	99.6
300	129.93	138.91	18.94	27.27	37.12	48.5	61.4	75.8	91.7	109.1
350	151.58	150.04	20.46	29.46	40.10	52.4	66.3	81.8	99.0	117.8
400	173.24	160.40	21.87	31.49	42.87	56.0	70.9	87.5	105.9	126.0
450	194.89	170.13	23.20	33.40	45.47	59.4	75.2	92.8	112.3	133.6
500	216.54	179.33	24.45	35.21	47.93	62.6	79.2	97.8	118.4	140.8

Theoretical Velocity of Water Due to Head in Feet

Head in Feet	Theoretical Velocity		Head in Feet	Theoretical Velocity		Head in Feet	Theoretical Velocity	
	ft/s	ft/min		ft/s	ft/min		ft/s	ft/min
1	8.01	481	48	55.56	3334	95	78.16	4690
2	11.34	681	49	56.13	3368	96	78.57	4715
3	13.89	833	50	56.70	3403	97	78.98	4739
4	16.04	962	51	57.27	3436	98	79.39	4764
5	17.93	1076	52	57.83	3470	99	79.79	4788
6	19.64	1179	53	58.38	3503	100	80.19	4812
7	21.21	1273	54	58.93	3536	105	82.18	4931
8	22.68	1361	55	59.47	3569	110	84.11	5047
9	24.05	1444	56	60.01	3601	115	86.00	5160
10	25.36	1522	57	60.54	3633	120	87.85	5271
11	26.59	1596	58	61.07	3665	125	89.66	5380
12	27.78	1667	59	61.60	3696	130	91.44	5487
13	28.91	1735	60	62.12	3727	135	93.18	5591
14	30.00	1800	61	62.63	3758	140	94.89	5694
15	31.06	1864	62	63.14	3789	145	96.57	5794
16	32.07	1925	63	63.65	3819	150	98.22	5893
17	33.06	1984	64	64.15	3850	155	99.84	5991
18	34.02	2042	65	64.65	3880	160	101.44	6087
19	34.95	2097	66	65.15	3909	165	103.01	6181
20	35.86	2152	67	65.64	3939	170	104.56	6274
21	36.75	2205	68	66.13	3968	175	106.09	6366
22	37.61	2257	69	66.61	3997	180	107.59	6456
23	38.46	2308	70	67.09	4026	185	109.08	6545
24	39.28	2357	71	67.57	4055	190	110.54	6633
25	40.09	2406	72	68.05	4083	195	111.99	6720
26	40.89	2454	73	68.52	4111	200	113.42	6805
27	41.67	2500	74	68.99	4139	205	114.82	6890
28	42.43	2546	75	69.45	4167	210	116.22	6973
29	43.18	2591	76	69.91	4195	215	117.59	7056
30	43.92	2636	77	70.37	4222	220	118.95	7137
31	44.65	2679	78	70.83	4250	225	120.30	7218
32	45.36	2722	79	71.28	4277	230	121.62	7298
33	46.07	2764	80	71.73	4304	235	122.94	7377
34	46.76	2806	81	72.17	4331	240	124.24	7455
35	47.44	2847	82	72.62	4357	245	125.53	7532
36	48.11	2887	83	73.06	4384	250	126.80	7608
37	48.78	2927	84	73.50	4410	255	128.06	7684
38	49.43	2966	85	73.94	4436	260	129.31	7759
39	50.08	3005	86	74.37	4462	270	131.78	7907
40	50.72	3043	87	74.80	4488	280	134.20	8052
41	51.35	3081	88	75.23	4514	290	136.57	8195
42	51.97	3119	89	75.66	4540	300	138.91	8335
43	52.59	3155	90	76.08	4565	310	141.20	8472
44	53.19	3192	91	76.50	4590	320	143.46	8608
45	53.79	3228	92	76.92	4615	330	145.69	8741
46	54.39	3264	93	77.34	4641	340	147.88	8873
47	54.98	3299	94	77.75	4665	350	150.04	9002

Gallons of Water per Foot of Pipe

Nominal Pipe Size (in.)	Iron or Steel		Copper		
	Sched. 40	Sched. 80	Type K	Type L	Type M
⅛	0.0030	0.0019	0.0014	0.0016	0.0016
¼	0.0054	0.0037	0.0039	0.0040	0.0043
⅜	0.0099	0.0073	0.0066	0.0075	0.0083
½	0.0158	0.0122	0.0113	0.0121	0.0132
⅝	…	…	0.0173	0.0181	0.0194
¾	0.0277	0.0225	0.0226	0.0251	0.0268
1	0.0449	0.0374	0.0404	0.0429	0.0454

Multiply the length of pipe in feet by the factor from the table to find the volume contained in gallons.

Friction Loss in Fittings—Equivalent Length of Pipe in Feet

Nominal Pipe Size (in.)	Elbows						Standard Tee	
	90° Std.	45° Std.	90° Long Radius	90° Street	45° Street	Square Corner	Flow thru Run	Flow thru Branch
¼	0.9	0.5	0.6	1.5	0.8	1.7	0.6	1.8
½	1.6	0.8	1.0	2.6	1.3	3.0	1.0	4.0
¾	2.1	1.1	1.4	3.4	1.8	3.9	1.4	5.1
1	2.6	1.4	1.7	4.4	2.3	5.0	1.7	6.0
1¼	3.5	1.8	2.3	5.8	3.0	6.5	2.3	6.9
1½	4.0	2.1	2.7	6.7	3.5	7.6	2.7	8.1
2	5.5	2.8	4.3	8.6	4.5	9.8	4.3	12.0
2½	6.2	3.3	5.1	10.3	5.4	11.7	5.1	14.3
3	7.7	4.1	6.3	12.8	6.6	14.6	6.3	16.3
4	10.1	5.4	8.3	16.8	8.7	19.1	8.3	22.1
6	15.2	8.1	12.5	25.3	13.1	28.8	12.5	32.2
8	20.0	10.6	16.5	33.3	17.3	37.9	16.5	39.9
10	25.1	13.4	20.7	41.8	21.7	47.6	20.7	50.1
12	29.8	15.9	24.7	49.7	25.9	56.7	24.7	59.7

Pipe Expansion Due to Temperature Changes.—The expansion for any length of pipe caused by a given temperature change can be determined from the following table. Find the expansion factor corresponding to the expected difference in the minimum and maximum pipe temperatures and divide by 100 to obtain the increase in length per foot of pipe. Multiply the increase per foot result by the length of the pipe run to get the total change in pipe length.

Linear Expansion and Contraction Factors per 100 Feet of Pipe

Temperature Change, °F	Pipe Material				
	Steel	Copper	PVC	FRP	PP & PVDF
0	0	0	0	0	0
20	0.15	0.25	0.62	0.26	2.00
40	0.30	0.45	1.30	0.52	4.00
60	0.46	0.65	2.20	0.78	6.00
80	0.61	0.87	2.80	1.05	8.00
100	0.77	1.10	3.50	1.31	10.00
120	0.92	1.35	4.25	1.57	12.00
140	1.08	1.57	4.80	1.83	14.00
160	1.24	1.77	5.50	2.09	16.00
180	1.40	2.00	6.30	2.35	18.00
200	1.57	2.25	7.12	2.62	20.00

Multiply the length of pipe by the table factor and divide by 100 for the increase or decrease in length.

Properties, Compression, and Flow of Air

Properties of Air.—Air is a mechanical mixture composed of 78 per cent of nitrogen, 21 per cent of oxygen, and 1 per cent of argon, by volume. The density of dry air at 32 degrees F and atmospheric pressure (29.92 inches of mercury or 14.70 pounds per square inch) is 0.08073 pound per cubic foot. The density of air at any other temperature or pressure is

$$\rho = \frac{1.325 \times B}{T}$$

in which ρ = density in pounds per cubic foot; B = height of barometric pressure in inches of mercury; T = absolute temperature in degrees Rankine. (When using pounds as a unit, here and elsewhere, care must be exercised to differentiate between pounds mass and pounds force. See *Acceleration of Gravity g Used in Mechanics Formulas* on page 114 and *The Use of the Metric SI System in Mechanics Calculations* on page 116.)

Volumes and Weights of Air at Different Temperatures, at Atmospheric Pressure

Temperature, °F	Volume of 1 lb of Air in Cubic Feet	Density, Pounds per Cubic Foot	Temperature, °F	Volume of 1 lb of Air in Cubic Feet	Density, Pounds per Cubic Foot	Temperature, °F	Volume of 1 lb of Air in Cubic Feet	Density, Pounds per Cubic Foot
0	11.57	0.0864	172	15.92	0.0628	800	31.75	0.0315
12	11.88	0.0842	182	16.18	0.0618	900	34.25	0.0292
22	12.14	0.0824	192	16.42	0.0609	1000	37.31	0.0268
32	12.39	0.0807	202	16.67	0.0600	1100	39.37	0.0254
42	12.64	0.0791	212	16.92	0.0591	1200	41.84	0.0239
52	12.89	0.0776	230	17.39	0.0575	1300	44.44	0.0225
62	13.14	0.0761	250	17.89	0.0559	1400	46.95	0.0213
72	13.39	0.0747	275	18.52	0.0540	1500	49.51	0.0202
82	13.64	0.0733	300	19.16	0.0522	1600	52.08	0.0192
92	13.89	0.0720	325	19.76	0.0506	1700	54.64	0.0183
102	14.14	0.0707	350	20.41	0.0490	1800	57.14	0.0175
112	14.41	0.0694	375	20.96	0.0477	2000	62.11	0.0161
122	14.66	0.0682	400	21.69	0.0461	2200	67.11	0.0149
132	14.90	0.0671	450	22.94	0.0436	2400	72.46	0.0138
142	15.17	0.0659	500	24.21	0.0413	2600	76.92	0.0130
152	15.41	0.0649	600	26.60	0.0376	2800	82.64	0.0121
162	15.67	0.0638	700	29.59	0.0338	3000	87.72	0.0114

The absolute zero from which all temperatures must be counted when dealing with the weight and volume of gases is assumed to be −459.7 degrees F. Hence, to obtain the absolute temperature T used in preceding formula, add the value 459.7 to the temperature observed on a regular Fahrenheit thermometer.

In obtaining the value of B, 1 inch of mercury at 32 degrees F may be taken as equal to a pressure of 0.491 pound per square inch.

Example: What would be the weight of a cubic foot of air at atmospheric pressure (29.92 inches of mercury) at 100 degrees F? The weight, W, is given by $W = \rho V$.

$$W = \rho V = \frac{1.325 \times 29.92}{100 + 459.7} \times 1 = 0.0708 \text{ pound}$$

Density of Air at Different Pressures and Temperatures

Temp. of Air, °F	Gage Pressure, Pounds														
	0	5	10	20	30	40	50	60	80	100	120	150	200	250	300
	Density in Pounds per Cubic Foot														
-20	0.0900	0.1205	0.1515	0.2125	0.274	0.336	0.397	0.458	0.580	0.702	0.825	1.010	1.318	1.625	1.930
-10	0.0882	0.1184	0.1485	0.2090	0.268	0.328	0.388	0.448	0.567	0.687	0.807	0.989	1.288	1.588	1.890
0	0.0864	0.1160	0.1455	0.2040	0.263	0.321	0.380	0.438	0.555	0.672	0.790	0.968	1.260	1.553	1.850
10	0.0846	0.1136	0.1425	0.1995	0.257	0.314	0.372	0.429	0.543	0.658	0.774	0.947	1.233	1.520	1.810
20	0.0828	0.1112	0.1395	0.1955	0.252	0.307	0.364	0.420	0.533	0.645	0.757	0.927	1.208	1.489	1.770
30	0.0811	0.1088	0.1366	0.1916	0.246	0.301	0.357	0.412	0.522	0.632	0.742	0.908	1.184	1.460	1.735
40	0.0795	0.1067	0.1338	0.1876	0.241	0.295	0.350	0.404	0.511	0.619	0.727	0.890	1.161	1.431	1.701
50	0.0780	0.1045	0.1310	0.1839	0.237	0.290	0.343	0.396	0.501	0.607	0.713	0.873	1.139	1.403	1.668
60	0.0764	0.1025	0.1283	0.1803	0.232	0.284	0.336	0.388	0.493	0.596	0.700	0.856	1.116	1.376	1.636
80	0.0736	0.0988	0.1239	0.1738	0.224	0.274	0.324	0.374	0.473	0.572	0.673	0.824	1.074	1.325	1.573
100	0.0710	0.0954	0.1197	0.1676	0.215	0.264	0.312	0.360	0.455	0.551	0.648	0.794	1.035	1.276	1.517
120	0.0680	0.0921	0.1155	0.1618	0.208	0.255	0.302	0.348	0.440	0.533	0.626	0.767	1.001	1.234	1.465
140	0.0663	0.0889	0.1115	0.1565	0.201	0.246	0.291	0.336	0.426	0.516	0.606	0.742	0.968	1.194	1.416
150	0.0652	0.0874	0.1096	0.1541	0.198	0.242	0.286	0.331	0.419	0.508	0.596	0.730	0.953	1.175	1.392
175	0.0626	0.0840	0.1054	0.1482	0.191	0.233	0.275	0.318	0.403	0.488	0.573	0.701	0.914	1.128	1.337
200	0.0603	0.0809	0.1014	0.1427	0.184	0.225	0.265	0.305	0.388	0.470	0.552	0.674	0.879	1.084	1.287
225	0.0581	0.0779	0.0976	0.1373	0.177	0.216	0.255	0.295	0.374	0.452	0.531	0.649	0.846	1.043	1.240
250	0.0560	0.0751	0.0941	0.1323	0.170	0.208	0.247	0.284	0.360	0.436	0.513	0.627	0.817	1.007	1.197
275	0.0541	0.0726	0.0910	0.1278	0.164	0.201	0.238	0.274	0.348	0.421	0.494	0.605	0.789	0.972	1.155
300	0.0523	0.0707	0.0881	0.1237	0.159	0.194	0.230	0.265	0.336	0.407	0.478	0.585	0.762	0.940	1.118
350	0.0491	0.0658	0.0825	0.1160	0.149	0.183	0.216	0.249	0.316	0.382	0.449	0.549	0.715	0.883	1.048
400	0.0463	0.0621	0.0779	0.1090	0.140	0.172	0.203	0.235	0.297	0.360	0.423	0.517	0.674	0.831	0.987
450	0.0437	0.0586	0.0735	0.1033	0.133	0.163	0.192	0.222	0.281	0.340	0.399	0.488	0.637	0.786	0.934
500	0.0414	0.0555	0.0696	0.978	0.126	0.154	0.182	0.210	0.266	0.322	0.379	0.463	0.604	0.746	0.885
550	0.0394	0.0528	0.0661	0.930	0.120	0.146	0.173	0.200	0.253	0.306	0.359	0.440	0.573	0.749	0.841
600	0.0376	0.0504	0.0631	0.885	0.114	0.139	0.165	0.190	0.241	0.292	0.343	0.419	0.547	0.675	0.801

Relation Between Pressure, Temperature, and Volume of Air.—This relationship is expressed by the formula:

$$\frac{P \times V}{T} = 53.3$$

in which P = absolute pressure in pounds per square foot; V = volume in cubic feet of one pound of air at the given pressure and temperature; T = absolute temperature in degrees R.

Example: What is the volume of one pound of air at a pressure of 24.7 pounds per square inch and at a temperature of 210 degrees F?

$$\frac{24.7 \times 144 \times V}{210 + 459.7} = 53.3 \text{ or } V = \frac{53.3 \times 669.7}{24.7 \times 144} = 10.04 \text{ cubic feet}$$

Relation Between Barometric Pressure, and Pressures in Pounds per Square Inch and Square Foot

Barometer, Inches	Pressure in Pounds per Square Inch	Pressure in Pounds per Square Foot	Barometer, Inches	Pressure in Pounds per Square Inch	Pressure in Pounds per Square Foot	Barometer, Inches	Pressure in Pounds per Square Inch	Pressure in Pounds per Square Foot
28.00	13.75	1980	29.25	14.36	2068	30.50	14.98	2156
28.25	13.87	1997	29.50	14.48	2086	30.75	15.10	2174
28.50	13.99	2015	29.75	14.61	2103	31.00	15.22	2192
28.75	14.12	2033	30.00	14.73	2121	31.25	15.34	2210
29.00	14.24	2050	30.25	14.85	2139	…	…	…

Expansion and Compression of Air.—The formula for the relationship between pressure, temperature, and volume of air just given indicates that when the pressure remains constant the volume is directly proportional to the absolute temperature. If the temperature remains constant, the volume is inversely proportional to the absolute pressure. Theoretically, air (as well as other gases) can be expanded or compressed according to different laws. *Adiabatic* expansion or compression takes place when the air is expanded or compressed without transmission of heat to or from it, as, for example, if the air could be expanded or compressed in a cylinder of an absolutely nonconducting material.

Let: P_1 = initial absolute pressure in pounds per square foot
V_1 = initial volume in cubic feet
T_1 = initial absolute temperature in degrees R
P_2 = absolute pressure in pounds per square foot, after compression
V_2 = volume in cubic feet, after compression
T_2 = absolute temperature in degrees R, after compression

Then:

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{0.71} \qquad \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{1.41} \qquad \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{0.41}$$

$$\frac{V_2}{V_1} = \left(\frac{T_1}{T_2}\right)^{2.46} \qquad \frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{3.46} \qquad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{0.29}$$

These formulas are also applicable if all pressures are in pounds per square inch; if all volumes are in cubic inches; or if any other consistent set of units is used for pressure or volume.

Isothermal: expansion or compression takes place when a gas is expanded or compressed with an addition or transmission of sufficient heat to maintain a constant temperature.

Let: P_1 = initial absolute pressure in pounds per square foot
V_1 = initial volume in cubic feet
P_2 = absolute pressure in pounds per square foot, after compression
V_2 = volume in cubic feet, after compression
R = 53.3
T = temperature in degrees Rankine maintained during isothermal expansion or contraction

Then:

$$P_1 \times V_1 = P_2 \times V_2 = RT$$

Example: A volume of 165 cubic feet of air, at a pressure of 15 pounds per square inch, is compressed adiabatically to a pressure of 80 pounds per square inch. What will be the volume at this pressure?

$$V_2 = V_1 \left(\frac{P_1}{P_2}\right)^{0.71} = 165\left(\frac{15}{80}\right)^{0.71} = 50 \text{ cubic feet, approx.}$$

Example: The same volume of air is compressed isothermally from 15 to 80 pounds per square inch. What will be the volume after compression?

$$V_2 = \frac{P_1 \times V_1}{P_2} = \frac{15 \times 165}{80} = 31 \text{ cubic feet}$$

Foot-pounds of Work Required in Compression of Air
Initial Pressure = 1 atmosphere = 14.7 pounds per square inch

Gage Pressure in Pounds per Square Inch	Isothermal Compression	Adiabatic Compression	Actual Compression	Gage Pressure in Pounds per Square Inch	Isothermal Compression	Adiabatic Compression	Actual Compression
	Foot-pounds Required per Cubic Foot of Air at Initial Pressure				Foot-pounds Required per Cubic Foot of Air at Initial Pressure		
5	619.6	649.5	637.5	55	3393.7	4188.9	3870.8
10	1098.2	1192.0	1154.6	60	3440.4	4422.8	4029.8
15	1488.3	1661.2	1592.0	65	3577.6	4645.4	4218.2
20	1817.7	2074.0	1971.4	70	3706.3	4859.6	4398.1
25	2102.6	2451.6	2312.0	75	3828.0	5063.9	4569.5
30	2353.6	2794.0	2617.8	80	3942.9	5259.7	4732.9
35	2578.0	3111.0	2897.8	85	4051.5	5450.0	4890.1
40	2780.8	3405.5	3155.6	90	4155.7	5633.1	5042.1
45	2966.0	3681.7	3395.4	95	4254.3	5819.3	5187.3
50	3136.2	3942.3	3619.8	100	4348.1	5981.2	5327.9

Work Required in Compression of Air.—The total work required for compression and expulsion of air, adiabatically compressed, is:

$$\text{Total work in foot-pounds} = 3.46 P_1 V_1\left[\left(\frac{P_2}{P_1}\right)^{0.29} - 1\right]$$

where P_1 = initial absolute pressure in pounds per square foot
P_2 = absolute pressure in pounds per square foot, after compression
V_1 = initial volume in cubic feet

The total work required for isothermal compression is:

$$\text{Total work in foot-pounds} = P_1 V_1 \log_e \frac{V_1}{V_2}$$

in which P_1, P_2, and V_1 denote the same quantities as in the previous equation, and V_2 = volume of air in cubic feet, after compression.

The work required to compress air isothermally, that is, when the heat of compression is removed as rapidly as produced, is considerably less than the work required for compressing air adiabatically, or when all the heat is retained. In practice, neither of these two theoretical extremes is obtainable, but the power required for air compression is about the median between the powers that would be required for each. The accompanying table gives the average number of foot-pounds of work required to compress air.

Horsepower Required to Compress Air.—In the accompanying tables is given the horsepower required to compress one cubic foot of free air per minute (isothermally and adiabatically) from atmospheric pressure (14.7 pounds per square inch) to various gage pressures, for one-, two-, and three-stage compression. The formula for calculating the horsepower required to compress, adiabatically, a given volume of free air to a given pressure is:

$$\text{HP} = \frac{144NPVn}{33{,}000(n-1)}\left[\left(\frac{P_2}{P}\right)^{\frac{n-1}{Nn}} - 1\right]$$

where N = number of stages in which compression is accomplished

P = atmospheric pressure in pounds per square inch

P_2 = absolute terminal pressure in pounds per square inch

V = volume of air, in cubic feet, compressed per minute, at atmospheric pressure

n = exponent of the compression curve = 1.41 for adiabatic compression

For different methods of compression and for one cubic foot of air per minute, this formula may be simplified as follows:

For one-stage compression: $\text{HP} = 0.015P(R^{0.29} - 1)$

For two-stage compression: $\text{HP} = 0.030\,P(R^{0.145} - 1)$

For three-stage compression: $\text{HP} = 0.045\,P(R^{0.0975} - 1)$

For four-stage compression: $\text{HP} = 0.060\,P(R^{0.0725} - 1)$

In these latter formulas $R = \frac{P_2}{P}$ = number of atmospheres to be compressed

The formula for calculating the horsepower required to compress isothermally a given volume of free air to a given pressure is:

$$\text{HP} = \frac{144PV}{33000}\left(\log_e \frac{P_2}{P}\right)$$

Natural logarithms are obtained by multiplying common logarithms by 2.30259 or by using a handheld calculator.

Horsepower Required to Compress Air

Horsepower Required To Compress One Cubic Foot of Free Air per Minute (Isothermally and Adiabatically) from Atmospheric Pressure (14.7 pounds per square inch) to Various Gage Pressures. — Single-Stage Compression (Initial Temperature of Air, 60°F — Jacket cooling not considered)								
Gage Pressure, Pounds	Absolute Pressure, Pounds	Number of Atmospheres	Isothermal Compression		Adiabatic Compression			
			Mean Effective Pressure[a]	Horsepower	Mean Effective Pressure,[a] Theoretical	Mean Eff. Pressure plus 15 per cent Friction	Horsepower, Theoretical	Horsepower plus 15 per cent Friction
5	19.7	1.34	4.13	0.018	4.46	5.12	0.019	0.022
10	24.7	1.68	7.57	0.033	8.21	9.44	0.036	0.041
15	29.7	2.02	11.02	0.048	11.46	13.17	0.050	0.057
20	34.7	2.36	12.62	0.055	14.30	16.44	0.062	0.071
25	39.7	2.70	14.68	0.064	16.94	19.47	0.074	0.085
30	44.7	3.04	16.30	0.071	19.32	22.21	0.084	0.096
35	49.7	3.38	17.90	0.078	21.50	24.72	0.094	0.108
40	54.7	3.72	19.28	0.084	25.53	27.05	0.103	0.118
45	59.7	4.06	20.65	0.090	25.40	29.21	0.111	0.127
50	64.7	4.40	21.80	0.095	27.23	31.31	0.119	0.136
55	69.7	4.74	22.95	0.100	28.90	33.23	0.126	0.145
60	74.7	5.08	23.90	0.104	30.53	35.10	0.133	0.153
65	79.7	5.42	24.80	0.108	32.10	36.91	0.140	0.161
70	84.7	5.76	25.70	0.112	33.57	38.59	0.146	0.168
75	89.7	6.10	26.62	0.116	35.00	40.25	0.153	0.175
80	94.7	6.44	27.52	0.120	36.36	41.80	0.159	0.182
85	99.7	6.78	28.21	0.123	37.63	43.27	0.164	0.189
90	104.7	7.12	28.93	0.126	38.89	44.71	0.169	0.195
95	109.7	7.46	29.60	0.129	40.11	46.12	0.175	0.201
100	114.7	7.80	30.30	0.132	41.28	47.46	0.180	0.207
110	124.7	8.48	31.42	0.137	43.56	50.09	0.190	0.218
120	134.7	9.16	32.60	0.142	45.69	52.53	0.199	0.229
130	144.7	9.84	33.75	0.147	47.72	54.87	0.208	0.239
140	154.7	10.52	34.67	0.151	49.64	57.08	0.216	0.249
150	164.7	11.20	35.59	0.155	51.47	59.18	0.224	0.258
160	174.7	11.88	36.30	0.158	53.70	61.80	0.234	0.269
170	184.7	12.56	37.20	0.162	55.60	64.00	0.242	0.278
180	194.7	13.24	38.10	0.166	57.20	65.80	0.249	0.286
190	204.7	13.92	38.80	0.169	58.80	67.70	0.256	0.294
200	214.7	14.60	39.50	0.172	60.40	69.50	0.263	0.303

[a] Mean Effective Pressure (MEP) is defined as that single pressure rise, above atmospheric, which would require the same horsepower as the actual varying pressures during compression.

Horsepower Required to Compress Air

Horsepower Required to Compress One Cubic Foot of Free Air per Minute (Isothermally and Adiabatically) from Atmospheric Pressure (14.7 pounds per square inch) to Various Gage Pressures.—Two-Stage Compression

(Initial Temperature of Air, 60°F —Jacket cooling not considered)

Gage Pressure, Pounds	Absolute Pressure, Pounds	Number of Atmospheres	Correct Ratio of Cylinder Volumes	Intercooler Gage Pressure	Isothermal Compression		Adiabatic Compression				Percentage of Saving over One-stage Compression
					Mean Effective Pressure[a]	Horsepower	Mean Eff. Pressure,[a] Theoretical	Mean Eff. Pressure plus 15 per cent Friction	Horsepower, Theoretical	HP plus 15 per cent Friction	
50	64.7	4.40	2.10	16.2	21.80	0.095	24.30	27.90	0.106	0.123	10.9
60	74.7	5.08	2.25	18.4	23.90	0.104	27.20	31.30	0.118	0.136	11.3
70	84.7	5.76	2.40	20.6	25.70	0.112	29.31	33.71	0.128	0.147	12.3
80	94.7	6.44	2.54	22.7	27.52	0.120	31.44	36.15	0.137	0.158	13.8
90	104.7	7.12	2.67	24.5	28.93	0.126	33.37	38.36	0.145	0.167	14.2
100	114.7	7.80	2.79	26.3	30.30	0.132	35.20	40.48	0.153	0.176	15.0
110	124.7	8.48	2.91	28.1	31.42	0.137	36.82	42.34	0.161	0.185	15.2
120	134.7	9.16	3.03	29.8	32.60	0.142	38.44	44.20	0.168	0.193	15.6
130	144.7	9.84	3.14	31.5	33.75	0.147	39.86	45.83	0.174	0.200	16.3
140	154.7	10.52	3.24	32.9	34.67	0.151	41.28	47.47	0.180	0.207	16.7
150	164.7	11.20	3.35	34.5	35.59	0.155	42.60	48.99	0.186	0.214	16.9
160	174.7	11.88	3.45	36.1	36.30	0.158	43.82	50.39	0.191	0.219	18.4
170	184.7	12.56	3.54	37.3	37.20	0.162	44.93	51.66	0.196	0.225	19.0
180	194.7	13.24	3.64	38.8	38.10	0.166	46.05	52.95	0.201	0.231	19.3
190	204.7	13.92	3.73	40.1	38.80	0.169	47.16	54.22	0.206	0.236	19.5
200	214.7	14.60	3.82	41.4	39.50	0.172	48.18	55.39	0.210	0.241	20.1
210	224.7	15.28	3.91	42.8	40.10	0.174	49.35	56.70	0.216	0.247	…
220	234.7	15.96	3.99	44.0	40.70	0.177	50.30	57.70	0.220	0.252	…
230	244.7	16.64	4.08	45.3	41.30	0.180	51.30	59.10	0.224	0.257	…
240	254.7	17.32	4.17	46.6	41.90	0.183	52.25	60.10	0.228	0.262	…
250	264.7	18.00	4.24	47.6	42.70	0.186	52.84	60.76	0.230	0.264	…
260	274.7	18.68	4.32	48.8	43.00	0.188	53.85	62.05	0.235	0.270	…
270	284.7	19.36	4.40	50.0	43.50	0.190	54.60	62.90	0.238	0.274	…
280	294.7	20.04	4.48	51.1	44.00	0.192	55.50	63.85	0.242	0.278	…
290	304.7	20.72	4.55	52.2	44.50	0.194	56.20	64.75	0.246	0.282	…
300	314.7	21.40	4.63	53.4	45.80	0.197	56.70	65.20	0.247	0.283	…
350	364.7	24.80	4.98	58.5	47.30	0.206	60.15	69.16	0.262	0.301	…
400	414.7	28.20	5.31	63.3	49.20	0.214	63.19	72.65	0.276	0.317	…
450	464.7	31.60	5.61	67.8	51.20	0.223	65.93	75.81	0.287	0.329	…
500	514.7	35.01	5.91	72.1	52.70	0.229	68.46	78.72	0.298	0.342	…

[a] Mean Effective Pressure (MEP) is defined as that single pressure rise, above atmospheric, which would require the same horsepower as the actual varying pressures during compression.

Horsepower Required to Compress Air

Horsepower Required for Compressing One Cubic Foot of Free Air per Minute (Isothermally and Adiabatically) from Atmospheric Pressure (14.7 pounds per square inch) to Various Gage Pressures.—Three-stage Compression (Initial Temperature of Air, 60°F.—Jacket-cooling not considered)

Gage Pressure, Pounds	Absolute Pressure, Pounds	Number of Atmospheres	Correct Ratio of Cylinder Volumes	Intercooler Gage Pressure, First and Second Stages	Isothermal Compression		Adiabatic Compression				Percentage of Saving over Two-stage Compression
					Mean Effective Pressure[a]	Horsepower	Mean Eff. Pressure,[a] Theoretical	Mean Eff. Pressure plus 15 per cent Friction	Horsepower Theoretical	HP plus 15 per cent Friction	
100	114.7	7.8	1.98	14.4– 42.9	30.30	0.132	33.30	38.30	0.145	0.167	5.23
150	164.7	11.2	2.24	18.2– 59.0	35.59	0.155	40.30	46.50	0.175	0.202	5.92
200	214.7	14.6	2.44	21.2– 73.0	39.50	0.172	45.20	52.00	0.196	0.226	6.67
250	264.7	18.0	2.62	23.8– 86.1	42.70	0.186	49.20	56.60	0.214	0.246	6.96
300	314.7	21.4	2.78	26.1– 98.7	45.30	0.197	52.70	60.70	0.229	0.264	7.28
350	364.7	24.8	2.92	28.2–110.5	47.30	0.206	55.45	63.80	0.242	0.277	7.64
400	414.7	28.2	3.04	30.0–121.0	49.20	0.214	58.25	66.90	0.253	0.292	8.33
450	464.7	31.6	3.16	31.8–132.3	51.20	0.223	60.40	69.40	0.263	0.302	8.36
500	514.7	35.0	3.27	33.4–142.4	52.70	0.229	62.30	71.70	0.273	0.314	8.38
550	564.7	38.4	3.38	35.0–153.1	53.75	0.234	65.00	74.75	0.283	0.326	8.80
600	614.7	41.8	3.47	36.3–162.3	54.85	0.239	66.85	76.90	0.291	0.334	8.86
650	664.7	45.2	3.56	37.6–171.5	56.00	0.244	67.90	78.15	0.296	0.340	9.02
700	714.7	48.6	3.65	38.9–180.8	57.15	0.249	69.40	79.85	0.303	0.348	9.18
750	764.7	52.0	3.73	40.1–189.8	58.10	0.253	70.75	81.40	0.309	0.355	…
800	814.7	55.4	3.82	41.4–199.5	59.00	0.257	72.45	83.25	0.315	0.362	…
850	864.7	58.8	3.89	42.5–207.8	60.20	0.262	73.75	84.90	0.321	0.369	…
900	914.7	62.2	3.95	43.4–214.6	60.80	0.265	74.80	86.00	0.326	0.375	…
950	964.7	65.6	4.03	44.6–224.5	61.72	0.269	76.10	87.50	0.331	0.381	…
1000	1014.7	69.0	4.11	45.7–233.3	62.40	0.272	77.20	88.80	0.336	0.383	…
1050	1064.7	72.4	4.15	46.3–238.3	63.10	0.275	78.10	90.10	0.340	0.391	…
1100	1114.7	75.8	4.23	47.5–248.3	63.80	0.278	79.10	91.10	0.344	0.396	…
1150	1164.7	79.2	4.30	48.5–256.8	64.40	0.281	80.15	92.20	0.349	0.401	…
1200	1214.7	82.6	4.33	49.0–261.3	65.00	0.283	81.00	93.15	0.353	0.405	…
1250	1264.7	86.0	4.42	50.3–272.3	65.60	0.286	82.00	94.30	0.357	0.411	…
1300	1314.7	89.4	4.48	51.3–280.8	66.30	0.289	82.90	95.30	0.362	0.416	…
1350	1364.7	92.8	4.53	52.0–287.3	66.70	0.291	84.00	96.60	0.366	0.421	…
1400	1414.7	96.2	4.58	52.6–293.5	67.00	0.292	84.60	97.30	0.368	0.423	…
1450	1464.7	99.6	4.64	53.5–301.5	67.70	0.295	85.30	98.20	0.371	0.426	…
1500	1514.7	103.0	4.69	54.3–309.3	68.30	0.298	85.80	98.80	0.374	0.430	…
1550	1564.7	106.4	4.74	55.0–317.3	68.80	0.300	86.80	99.85	0.378	0.434	…
1600	1614.7	109.8	4.79	55.8–323.3	69.10	0.302	87.60	100.80	0.382	0.438	…

[a] Mean Effective Pressure (MEP) is defined as that single pressure rise, above atmospheric, which would require the same horsepower as the actual varying pressures during compression.

Flow of Air in Pipes.—The following formulas are used:

$$v = \sqrt{\frac{25,000\ dp}{L}} \qquad p = \frac{Lv^2}{25,000\ d}$$

where v = velocity of air in feet per second
p = loss of pressure due to flow through the pipes in ounces per square inch
d = inside diameter of pipe in inches
L = length of pipe in feet

The quantity of air discharged in cubic feet per second is the product of the velocity as obtained from the preceding formula and the area of the pipe in square feet. The horsepower required to drive air through a pipe equals the volume of air in cubic feet per second multiplied by the pressure in pounds per square foot, and this product divided by 550.

Volume of Air Transmitted Through Pipes, in Cubic Feet per Minute

Velocity of Air in Feet per Second	Actual Inside Diameter of Pipe, Inches									
	1	2	3	4	6	8	10	12	16	24
1	0.33	1.31	2.95	5.2	11.8	20.9	32.7	47.1	83.8	188
2	0.65	2.62	5.89	10.5	23.6	41.9	65.4	94.2	167.5	377
3	0.98	3.93	8.84	15.7	35.3	62.8	98.2	141.4	251.3	565
4	1.31	5.24	11.78	20.9	47.1	83.8	131.0	188.0	335.0	754
5	1.64	6.55	14.7	26.2	59.0	104.0	163.0	235.0	419.0	942
6	1.96	7.85	17.7	31.4	70.7	125.0	196.0	283.0	502.0	1131
7	2.29	9.16	20.6	36.6	82.4	146.0	229.0	330.0	586.0	1319
8	2.62	10.50	23.5	41.9	94.0	167.0	262.0	377.0	670.0	1508
9	2.95	11.78	26.5	47.0	106.0	188.0	294.0	424.0	754.0	1696
10	3.27	13.1	29.4	52.0	118.0	209.0	327.0	471.0	838.0	1885
12	3.93	15.7	35.3	63.0	141.0	251.0	393.0	565.0	1005.0	2262
15	4.91	19.6	44.2	78.0	177.0	314.0	491.0	707.0	1256.0	2827
18	5.89	23.5	53.0	94.0	212.0	377.0	589.0	848.0	1508.0	3393
20	6.55	26.2	59.0	105.0	235.0	419.0	654.0	942.0	1675.0	3770
24	7.86	31.4	71.0	125.0	283.0	502.0	785.0	1131.0	2010.0	4524
25	8.18	32.7	73.0	131.0	294.0	523.0	818.0	1178.0	2094.0	4712
28	9.16	36.6	82.0	146.0	330.0	586.0	916.0	1319.0	2346.0	5278
30	9.80	39.3	88.0	157.0	353.0	628.0	982.0	1414.0	2513.0	5655

Flow of Compressed Air in Pipes.—When there is a comparatively small difference of pressure at the two ends of the pipe, the volume of flow in cubic feet per minute is found by the formula:

$$V = 58\sqrt{\frac{pd^5}{WL}}$$

where V = volume of air in cubic feet per minute
p = difference in pressure at the two ends of the pipe in pounds per square inch
d = inside diameter of pipe in inches
W = weight in pounds of one cubic foot of entering air
L = length of pipe in feet

Velocity of Escaping Compressed Air.—If air, or gas, flows from one chamber to another, as from a chamber or tank through an orifice or nozzle into the open air, large changes in velocity may take place owing to the difference in pressures. Since the change takes place almost instantly, little heat can escape from the fluid and the flow may be assumed to be adiabatic.

For a large container with a small orifice or hole from which the air escapes, the velocity of escape (theoretical) may be calculated from the formula:

$$v_2 = \sqrt{2g \cdot \frac{k}{k-1} \cdot 53.3(459.7 + F)\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right]}$$

In this formula, v_2 = velocity of escaping air in feet per second; g = acceleration due to gravity, 32.16 feet per second squared; k = 1.41 for adiabatic expansion or compression of air; F = temperature, degrees F; p_2 = atmospheric pressure = 14.7 pounds per square inch; and p_1 = pressure of air in container, pounds per square inch. In applying the preceding formula, when the ratio p_2/p_1 approximately equals 0.53, under normal temperature conditions at sea level, the escape velocity v_2 will be equal to the velocity of sound. Increasing the pressure p_1 will not increase the velocity of escaping air beyond this limiting velocity unless a special converging diverging nozzle design is used rather than an orifice.

The accompanying table provides velocity of escaping air for various values of p_1. These values were calculated from the preceding formula simplified by substituting the appropriate constants:

$$v_2 = 108.58\sqrt{(459.7 + F)\left[1 - \left(\frac{14.7}{p_1}\right)^{0.29}\right]}$$

Velocity of Escaping Air at 70-Degrees F

Pressure Above Atmospheric Pressure			Theoretical Velocity, Feet per Second	Pressure Above Atmospheric Pressure			Theoretical Velocity, Feet per Second
In Atmospheres	In Inches Mercury	In lbs per sq. in.		In Atmospheres	In Inches Mercury	In lbs per sq. in.	
0.010	0.30	0.147	134	0.408	12.24	6.00	769
0.068	2.04	1.00	344	0.500	15.00	7.35	833
0.100	3.00	1.47	413	0.544	16.33	8.00	861
0.136	4.08	2.00	477	0.612	18.37	9.00	900
0.204	6.12	3.00	573	0.680	20.41	10.0	935
0.272	8.16	4.00	650	0.816	24.49	12.0	997
0.340	10.20	5.00	714	0.884	26.53	13.0	1025

The theoretical velocities in the preceding table must be reduced by multiplying by a "coefficient of discharge," which varies with the orifice and the pressure. The following coefficients are used for orifices in thin plates and short tubes.

Type of Orifice	Pressures in Atmospheres Above Atmospheric Pressure			
	0.01	0.1	0.5	1
Orifice in thin plate	0.65	0.64	0.57	0.54
Orifice in short tube	0.83	0.82	0.71	0.67