Appendix A
Altitude Tables

A.1 Units

Table A.1 British Engineering (BE) units[a]

h, kft	δ, P/P_{std}	Standard day θ, T/T_{std}	Cold day θ, T/T_{std}	Hot day θ, T/T_{std}	Tropical day θ, T/T_{std}	h, kft
0	1.0000	1.0000	0.7708	1.0849	1.0594	0
1	0.9644	0.9931	0.7972	1.0774	1.0520	1
2	0.9298	0.9863	0.8237	1.0700	1.0446	2
3	0.8963	0.9794	0.8501	1.0626	1.0372	3
4	0.8637	0.9725	0.8575	1.0552	1.0298	4
5	0.8321	0.9656	0.8575	1.0478	1.0224	5
6	0.8014	0.9588	0.8575	1.0404	1.0150	6
7	0.7717	0.9519	0.8575	1.0330	1.0076	7
8	0.7429	0.9450	0.8575	1.0256	1.0002	8
9	0.7149	0.9381	0.8575	1.0182	0.9928	9
10	0.6878	0.9313	0.8565	1.0108	0.9854	10
11	0.6616	0.9244	0.8502	1.0034	0.9780	11
12	0.6362	0.9175	0.8438	0.9960	0.9706	12
13	0.6115	0.9107	0.8375	0.9886	0.9632	13
14	0.5877	0.9038	0.8312	0.9812	0.9558	14
15	0.5646	0.8969	0.8248	0.9738	0.9484	15
16	0.5422	0.8901	0.8185	0.9664	0.9410	16
17	0.5206	0.8832	0.8121	0.9590	0.9336	17
18	0.4997	0.8763	0.8058	0.9516	0.9262	18
19	0.4795	0.8695	0.7994	0.9442	0.9188	19
20	0.4599	0.8626	0.7931	0.9368	0.9114	20
21	0.4410	0.8558	0.7867	0.9294	0.9040	21
22	0.4227	0.8489	0.7804	0.9220	0.8965	22
23	0.4051	0.8420	0.7740	0.9145	0.8891	23
24	0.3880	0.8352	0.7677	0.9071	0.8817	24
25	0.3716	0.8283	0.7613	0.8997	0.8743	25

(continued)

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Table A.1 **British Engineering (BE) units[a] (continued)**

h, kft	δ, P/P_{std}	Standard day θ, T/T_{std}	Cold day θ, T/T_{std}	Hot day θ, T/T_{std}	Tropical day θ, T/T_{std}	h, kft
30	0.2975	0.7940	0.7296	0.8627	0.8373	30
31	0.2843	0.7872	0.7233	0.8553	0.8299	31
32	0.2715	0.7803	0.7222	0.8479	0.8225	32
33	0.2592	0.7735	0.7222	0.8405	0.8151	33
34	0.2474	0.7666	0.7222	0.8331	0.8077	34
35	0.2360	0.7598	0.7222	0.8257	0.8003	35
36	0.2250	0.7529	0.7222	0.8183	0.7929	36
37	0.2145	0.7519	0.7222	0.8109	0.7855	37
38	0.2044	0.7519	0.7222	0.8035	0.7781	38
39	0.1949	0.7519	0.7222	0.7961	0.7707	39
40	0.1858	0.7519	0.7222	0.7939	0.7633	40
42	0.1688	0.7519	0.7222	0.7956	0.7485	42
44	0.1534	0.7519	0.7095	0.7973	0.7337	44
46	0.1394	0.7519	0.6907	0.7989	0.7188	46
48	0.1267	0.7519	0.6719	0.8006	0.7040	48
50	0.1151	0.7519	0.6532	0.8023	0.6892	50
52	0.1046	0.7519	0.6452	0.8040	0.6744	52
54	0.09507	0.7519	0.6452	0.8057	0.6768	54
56	0.08640	0.7519	0.6452	0.8074	0.6849	56
58	0.07852	0.7519	0.6452	0.8091	0.6929	58
60	0.07137	0.7519	0.6452	0.8108	0.7009	60
62	0.06486	0.7519	0.6514	0.8125	0.7090	62
64	0.05895	0.7519	0.6609	0.8142	0.7170	64
66	0.05358	0.7521	0.6704	0.8159	0.7251	66
68	0.04871	0.7542	0.6799	0.8166	0.7331	68
70	0.04429	0.7563	0.6894	0.8196	0.7396	70
72	0.04028	0.7584	0.6990	0.8226	0.7448	72
74	0.03665	0.7605	0.7075	0.8255	0.7501	74
76	0.03336	0.7626	0.7058	0.8285	0.7553	76
78	0.03036	0.7647	0.7042	0.8315	0.7606	78
80	0.02765	0.7668	0.7026	0.8344	0.7658	80
82	0.02518	0.7689	0.7009	0.8374	0.7711	82
84	0.02294	0.7710	0.6993	0.8403	0.7763	84
86	0.02091	0.7731	0.6976	0.8433	0.7816	86
88	0.01906	0.7752	0.6960	0.8463	0.7868	88
90	0.01738	0.7772	0.6944	0.8492	0.7921	90
92	0.01585	0.7793	0.6927	0.8522	0.7973	92
94	0.01446	0.7814	0.6911	0.8552	0.8026	94
96	0.01320	0.7835	0.6894	0.8581	0.8078	96
98	0.01204	0.7856	0.6878	0.8611	0.8130	98
100	0.01100	0.7877	0.6862	0.8640	0.8183	100

[a]Density: $\rho = \rho_{std}\ \sigma = \rho_{std}(\delta/\theta)$. Speed of sound: $a = a_{std}\sqrt{\theta}$.
Reference values: $P_{std} = 2116.2$ lbf/ft^2; $T_{std} = 518.69$°R; $\rho_{std} = 0.07647$ lbm/ft^3; $a_{std} = 1116$ ft/s.

Table A.2 Système International (SI) units[a]

h, km	δ, P/P_{std}	Standard day θ, T/T_{std}	Cold day θ, T/T_{std}	Hot day θ, T/T_{std}	Tropical day θ, T/T_{std}	h, km
0	1.0000	1.0000	0.7708	1.0849	1.0594	0
0.25	0.9707	0.9944	0.7925	1.0788	1.0534	0.25
0.50	0.9421	0.9887	0.8142	1.0727	1.0473	0.50
0.75	0.9142	0.9831	0.8358	1.0666	1.0412	0.75
1.00	0.8870	0.9774	0.8575	1.0606	1.0352	1.00
1.25	0.8604	0.9718	0.8575	1.0545	1.0291	1.25
1.50	0.8345	0.9662	0.8575	1.0484	1.0230	1.50
1.75	0.8093	0.9605	0.8575	1.0423	1.0169	1.75
2.00	0.7846	0.9549	0.8575	1.0363	1.0109	2.00
2.25	0.7606	0.9493	0.8575	1.0302	1.0048	2.25
2.50	0.7372	0.9436	0.8575	1.0241	0.9987	2.50
2.75	0.7143	0.9380	0.8575	1.0180	0.9926	2.75
3.00	0.6920	0.9324	0.8575	1.0120	0.9866	3.00
3.25	0.6703	0.9267	0.8523	1.0059	0.9805	3.25
3.50	0.6492	0.9211	0.8471	0.9998	0.9744	3.50
3.75	0.6286	0.9155	0.8419	0.9938	0.9683	3.75
4.00	0.6085	0.9098	0.8367	0.9877	0.9623	4.00
4.25	0.5890	0.9042	0.8315	0.9816	0.9562	4.25
4.50	0.5700	0.8986	0.8263	0.9755	0.9501	4.50
4.75	0.5514	0.8929	0.8211	0.9695	0.9441	4.75
5.00	0.5334	0.8873	0.8159	0.9634	0.9380	5.00
5.25	0.5159	0.8817	0.8107	0.9573	0.9319	5.25
5.50	0.4988	0.8760	0.8055	0.9512	0.9258	5.50
5.75	0.4822	0.8704	0.8003	0.9452	0.9198	5.75
6.00	0.4660	0.8648	0.7951	0.9391	0.9137	6.00
6.25	0.4503	0.8592	0.7899	0.9330	0.9076	6.25
6.50	0.4350	0.8535	0.7847	0.9269	0.9015	6.50
6.75	0.4201	0.8479	0.7795	0.9209	0.8955	6.75
7.00	0.4057	0.8423	0.7742	0.9148	0.8894	7.00
7.25	0.3916	0.8366	0.7690	0.9087	0.8833	7.25
7.50	0.3780	0.8310	0.7638	0.9027	0.8773	7.50
7.75	0.3647	0.8254	0.7586	0.8966	0.8712	7.75
8.00	0.3519	0.8198	0.7534	0.8905	0.8651	8.00
8.25	0.3393	0.8141	0.7482	0.8844	0.8590	8.25
8.50	0.3272	0.8085	0.7430	0.8784	0.8530	8.50
8.75	0.3154	0.8029	0.7378	0.8723	0.8469	8.75
9.00	0.3040	0.7973	0.7326	0.8662	0.8408	9.00
9.25	0.2929	0.7916	0.7274	0.8601	0.8347	9.25
9.50	0.2821	0.7860	0.7222	0.8541	0.8287	9.50
9.75	0.2717	0.7804	0.7222	0.8480	0.8226	9.75
10.00	0.2615	0.7748	0.7222	0.8419	0.8165	10.00
10.25	0.2517	0.7692	0.7222	0.8358	0.8104	10.25
10.50	0.2422	0.7635	0.7222	0.8298	0.8044	10.50
10.75	0.2330	0.7579	0.7222	0.8237	0.7983	10.75
11.00	0.2240	0.7523	0.7222	0.8176	0.7922	11.00

(continued)

Table A.2 Système International (SI) units[a] (continued)

h, km	δ, P/P_{std}	Standard day θ, T/T_{std}	Cold day θ, T/T_{std}	Hot day θ, T/T_{std}	Tropical day θ, T/T_{std}	h, km
11.25	0.2154	0.7519	0.7222	0.8116	0.7862	11.25
11.50	0.2071	0.7519	0.7222	0.8055	0.7801	11.50
11.75	0.1991	0.7519	0.7222	0.7994	0.7740	11.75
12.00	0.1915	0.7519	0.7222	0.7933	0.7679	12.00
12.25	0.1841	0.7519	0.7222	0.7940	0.7619	12.25
12.50	0.1770	0.7519	0.7222	0.7947	0.7558	12.50
12.75	0.1702	0.7519	0.7222	0.7954	0.7497	12.75
13.00	0.1636	0.7519	0.7222	0.7961	0.7436	13.00
13.25	0.1573	0.7519	0.7145	0.7968	0.7376	13.25
13.50	0.1513	0.7519	0.7068	0.7975	0.7315	13.50
13.75	0.1454	0.7519	0.6991	0.7982	0.7254	13.75
14.00	0.1399	0.7519	0.6914	0.7989	0.7193	14.00
14.25	0.1345	0.7519	0.6837	0.7996	0.7133	14.25
14.50	0.1293	0.7519	0.6760	0.8003	0.7072	14.50
14.75	0.1243	0.7519	0.6683	0.8010	0.7011	14.75
15.00	0.1195	0.7519	0.6606	0.8017	0.6951	15.00
15.25	0.1149	0.7519	0.6529	0.8024	0.6890	15.25
15.50	0.1105	0.7519	0.6452	0.8031	0.6829	15.50
15.75	0.1063	0.7519	0.6452	0.8037	0.6768	15.75
16.0	0.1022	0.7519	0.6452	0.8044	0.6708	16.0
16.5	0.09447	0.7519	0.6452	0.8058	0.6774	16.5
17.0	0.08734	0.7519	0.6452	0.8072	0.6839	17.0
17.5	0.08075	0.7519	0.6452	0.8086	0.6905	17.5
18.0	0.07466	0.7519	0.6452	0.8100	0.6971	18.0
18.5	0.06903	0.7519	0.6452	0.8114	0.7037	18.5
19.0	0.06383	0.7519	0.6531	0.8128	0.7103	19.0
19.5	0.05902	0.7519	0.6611	0.8142	0.7169	19.5
20.0	0.05457	0.7519	0.6691	0.8155	0.7235	20.0
20.5	0.05046	0.7534	0.6771	0.8169	0.7301	20.5
21.0	0.04667	0.7551	0.6851	0.8180	0.7367	21.0
21.5	0.04317	0.7568	0.6930	0.8204	0.7410	21.5
22.0	0.03995	0.7585	0.7010	0.8228	0.7453	22.0
23	0.03422	0.7620	0.7063	0.8277	0.7539	23
24	0.02933	0.7654	0.7036	0.8326	0.7625	24
25	0.02516	0.7689	0.7009	0.8374	0.7711	25
26	0.02160	0.7723	0.6982	0.8423	0.7797	26
27	0.01855	0.7758	0.6955	0.8471	0.7883	27
28	0.01595	0.7792	0.6928	0.8520	0.7969	28
29	0.01372	0.7826	0.6901	0.8568	0.8056	29
30	0.01181	0.7861	0.6874	0.8617	0.8142	30

[a]Density: $\rho = \rho_{std}\ \sigma = \rho_{std}(\delta/\theta)$. Speed of sound: $a = a_{std}\sqrt{\theta}$.
Reference values: $P_{std} = 101{,}325\ \mathrm{N/m^2}$; $T_{std} = 288.15\ \mathrm{K}$; $\rho_{std} = 1.225\ \mathrm{kg/m^3}$; $a_{std} = 340.3\ \mathrm{m/s}$.

A.2 U.S. Bureau of Standards, Standard Atmosphere 1976

A computer model (e.g., ATMOS program) of the standard day atmosphere can be written from the following material extracted from Ref. 2. All of the following is limited to geometric altitudes below 86 km—the original tables go higher, up to 1000 km. In addition, the correction for variation in mean molecular weight with altitude is very small, below 86 km, and so it is neglected.

The geometric or actual altitude h is related to the geo-potential altitude z, only used for internal calculations (a correction for variation of acceleration of gravity, used only for pressure and density calculations), by

$$z = r_0 h/(r_0 + h)$$

where $r_0 =$ 6,356.577 km is the Earth's radius.

The variation of temperature T with geo-potential altitude is represented by a continuous, piecewise linear relation,

$$T = T_i + L_i(z - z_i), \quad i = 0 \text{ through } 7$$

with fit coefficients as shown in Table A.3.

With $T_0 = 288.15$ K given, the corresponding values of temperature T_i can be readily generated from the given piecewise linear curve-fit. Note that z_7 corresponds exactly to $h = 86$ km.

The corresponding pressure P, also a piecewise continuous function, is given by

$$P = P_i \left(\frac{T_i}{T}\right)^{\left(\frac{g_0 W_0}{R^* L_i}\right)}, \quad L_i \neq 0, \quad \text{or} \quad P = P_i \exp\left(\frac{-g_0 W_0 (z - z_i)}{R^* T_i}\right), \quad L_i = 0$$

where $g_0 = 9.80665\ \mathrm{m/s^2}$, $R^* = 8{,}314.32$ J/kmol-K, $W_0 = 28.9644$ kg/kmol, and the pressure calculations start from $P_0 = 101{,}325.0\ \mathrm{N/m^2}$.

Table A.3 Standard day temperature model

i	z_i, km	L_i, K/km
0	0	−6.5
1	11	0.0
2	20	+1.0
3	32	+2.8
4	47	0.0
5	51	−2.8
6	71	−2.0
7	84.852	——

Table A.4 Nonstandard day temperature models

	Cold day		Hot day		Tropical day	
i	h_i, km	L_i, K/km	h_i, km	L_i, K/km	h_i, km	L_i, K/km
0	0	+25	0	−7.0	0	−7.0
1	1	0	12	+0.8	16	+3.8
2	3	−6.0	20.5	+1.4	21	+2.48
3	9.5	0				
4	13	−8.88				
5	15.5	0				
6	18.5	+4.6				
7	22.5	−0.775				

The density ρ is given simply by the ideal gas law,

$$\rho = \frac{PW_0}{R^*T}$$

A.3 Cold, Hot, and Tropical Day Temperature Profiles

A computer model (e.g., ATMOS program) of the temperature profiles for cold, hot, and tropical days can be written from the following material extracted from linear curve-fits of the data in Refs. 85 and 86. The following is limited to pressure altitudes below 30.5 km. The variation of temperature T with pressure altitude is represented by a continuous, piecewise linear relation,

$$T = T_i + L_i(h - h_i), \qquad i = 0 \text{ through } 7$$

with fit coefficients as shown in Table A.4.

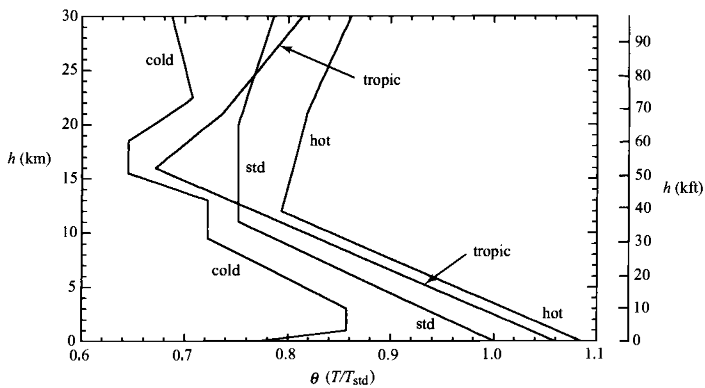

Fig. A.1 Four atmospheric temperature profiles vs pressure altitude h.

Table A.5 Sea-level base temperature

Day	Cold	Hot	Tropical
T_0, K	222.10	312.60	305.27

With T_0 given in Table A.5 for the respective temperature profile, the corresponding values of temperature T_i can be readily generated from the given piecewise linear curve-fit.

The pressure at the pressure altitude comes directly from the standard atmosphere calculation for the geometric or actual altitude h equal to that pressure altitude. Figure A.1 shows the three nonstandard day temperature profiles vs pressure altitude along with that of a standard day.

Appendix B
Gas Turbine Engine Data

Table B.1 Data for some military gas turbine engines

Model no.	Type	Max. thrust or power @ SLS	SFC[a] at max.	Airflow, lbm/s	OPR[b] (stages)[c]	Maximum D, in.	Maximum L, in.	Weight, lbf	TIT[d], °F	Application
J57-P-23	TJ[e]	16,000 lbf	2.10	165	11.5 (16)	40	246	5,169	1,600	AB, F-102A, F-100D
J57-P-43WB	TJ	11,200 lbf	0.775	180	12 (16)	39	167.3	3,870	1,600	Water-injected, KC-135
J58-P[f]	TJ	32,500 lbf	—	450	6 (9)	—	—	—	—	AB, YF-12A, SR-71
J60-P-3	TJ	3,000 lbf	0.96	50	7 (9)	23.4	79.5	460	1,600	T-39A, C-140A
J69-T-25	TJ	1,025 lbf	1.14	20.5	3.9 (0,1)	22.3	43.3	364	1,525	T-37B
J75-P-17	TJ	24,500 lbf	2.15	252	12.0 (15)	43	237.6	5,875	1,610	AB, F-106A/B
J79-GE-17	TJ	17,820 lbf	1.965	170	13.5 (17)	39.1	208.7	3,855	1,210	AB, F-4E/G
J85-GE-5H	TJ	3,850 lbf	2.20	44	7 (8)	20.4	109.1	584	1,640	AB, T-38A/B
J85-GE-17	TJ	2,850 lbf	0.99	44	7 (8)	17.7	40.4	395	1,640	A-37B
J85-GE-21	TJ	5,000 lbf	2.13	51.9	8 (8)	20	116	667	1,790	AB, F-5E/F
PT6A-42	TP[g]	850 eshp	0.601	8.0	8 (3,1)	19	67	391	—	C-12E
PT6A-45R	TP	1,197 eshp	0.553	8.6	8.7 (3,1)	19	72	434	—	C-23A
T400-CP-400	TS[h]	1,800 shp	0.606	6.51	7 (3,1)	43.5	66.3	716	1,920	Bell UH-1N

(continued)

Table B.1 Data for some military gas turbine engines (continued)

Model no.	Type	Max. thrust or power @ SLS	SFC[a] at max.	Airflow, lbm/s	OPR[b] (stages)[c]	Maximum		Weight, lbf	TIT[d], °F	Application
						D, in.	L, in.			
T406-AD-400	TS	6,150 shp	0.424	—	(14)	24.5	77.9	975	1,422	CV-22
T53-L-13	TS	1,400 shp	0.58	12.2	7 (5,1)	23	47.6	549	1,720	Bell UH-lH, AH-1G
T55-L-11	TS	3,750 shp	0.52	—	8 (6,1)	24.3	44	670	—	Boeing CH-47C
T56-A-7	TP	3,775 eshp	0.528	32.5	9.45 (14)	40.9	146	1,833	1,780	C-130B/E/F
T56-A-15	TP	4,591 eshp	0.54	32.5	9.55 (14)	44.6	146.3	1,848	1,970	C-130H/N/P
T58-GE-100	TS	1,500 shp	0.606	14	8.4 (10)	21.5	58.6	335	1,372	Sikorsky CH-3E, HH-3E, F
T64-GE-100	TS	4,330 shp	0.487	29.3	14 (14)	20.2	77.1	720	1,520	MH-53T
T700-GE-700	TS	1,622 shp	0.46	—	15 (5,1)	25	47	423	1,563	UH-60A
T76-G-10	TS	715 shp	0.60	6.16	8.6 (2)	27.1	44.5	348	1,818	OV-1OA

[a]SFC = specific fuel consumption. [b]OPR = overall pressure ratio. [c](stages) = (axial, centrifugal) compressor stages. [d]TIT = turbine inlet temperature. [e]TJ = turbojet. [f]J-58 Reference: Lockheed SR-71 by Jay Miller, Aerofax Minigraph 1, Aerofax, Inc., Arlington, TX, 1985. [g]TP = turboprop. [h]TS = turboshaft. (Sources: Manufacturers' literature).

Table B.2 Data for some military turbofan engines

Model no.	Thrust, lbf	TSFC[a], 1/h	Airflow, lbm/s	OPR[b]	Maximum *D*, in.	Maximum *L*, in.	Weight, lbf	TIT[c], °F	FPR[d]	BR[e]	Application
F100-PW-229	29,000	2.05	248	23.0	47	191	3,036	2,700	3.8	0.4	F-15, F16
	17,800	0.74									
F101-GE-102	30,780	2.460	356	26.8	55.2	180.7	4,448	2,550	2.31	1.91	B-1B
	17,390	0.562									
F103-GE-101	51,711	0.399	1,476	30.2	86.4	173	8,768	2,490	—	4.31	KC-10A
F107-WR-101	635	0.685	13.6	13.8	12	48.5	141	—	2.1	1.0	Air Launch Cruise Missile
F108-CF-100	21,634	0.363	785	23.7	72	115.4	4,610	2,228	1.5	6.0	KC-135R
F110-GE-100	28,620	2.08	254	30.4	46.5	182	3,895	—	2.98	0.80	F-16
	18,330	1.47									
F117-PW-100	41,700	0.33	—	31.8	84.5	146.8	7,100	—	—	5.8	(PW2040) C-17A
F118-GE-100	19,000	0.67	—	35.1	46.5	100.5	3,200	—	—	—	B-2
F119-PW-100	35,000	—	—	—	—	—	—	—	—	—	F-22 Rapton
F135-PW	40,000	—	—	—	—	—	—	—	—	—	F-35 JSF
F404-GE-FID	10,000	0.79	—	24	35	83	1,730	—	—	—	F-117A

(continued)

Table B.2 Data for some military gas turbine engines (continued)

					Maximum						
Model no.	Thrust, lbf	TSFC[a], 1/h	Airflow, lbm/s	OPR[b]	*D*, in.	*L*, in.	Weight, lbf	TIT[c], °F	FPR[d]	BR[e]	Application
F404-GE-400	16,000	1.85	142	26	35	154	—	—	—	0.34	F-18, F-5G
F414-GE-400	22,000	—	—	30	35	154	—	—	—	—	F/A-18E/F
JT3D-3B	18,000	0.535	458	13.6	53	136.4	4,300	1,600	1.74	1.37	(TF33-102) EC/RC-135
JT8D-7B	14,500	0.585	318	16.9	45	123.7	3.252	1,076		1.03	C-22, C-9, T-43A
TF30-P-111	25,100	2.450	260	21.8	49	241.7	3,999	2,055	2.43	0.73	F-111F
	14,560	0.686									
TF33-P-3	17,000	0.52	450	13.0	53	136	3,900	1,600	1.7	1.55	B-52H
TF33-P-7	21,000	0.56	498	16.0	54	142	4,650	1,750	1.9	1.21	C-141
TF34-GE-100	9.065	0.37	333	20.0	50	100	1,421	2,234	1.5	6.42	A-10
TF39-GE-1	40,805	0.315	1,549	26.0	100	203	7,186	2,350	1.56	8.0	C-5A
TF41-A-1B	14,500	0.647	260	20.0	40	114.5	3,511	2,165	2.45	0.76	A-7D, K
TFE731-2	3,500	0.504	113	17.7	40	50	625	—	1.54	2.67	C-21A

[a]TSFC = thrust specific fuel consumption. [b]OPR = overall pressure ratio. [c]TIT = turbine inlet temperature. [d]FPR = fan pressure ratio. [e]BR = bypass ratio. (Sources: Manufacturers' literature).

Table B.3 Data for some civil gas turbine engines

		Takeoff				Cruise				
Model no.	Manufacturer	Thrust, lbf	BR[a]	OPR[b]	Airflow, lbm/s	Alt, kft	Mach	Thrust, lbf	TSFC[c]	Application
CF 34-8	General Electric	14,500	5	28	—	—	—	—	0.68	Bombardier CRJ700 Embraer 170/175
CF6-50-C2	General Electric	52,500	4.31	30.4	1,476	35	0.80	11,555	0.630	DC10-10, A300B, 747-200
CF6-80-C2	General Electric	52,500	5.31	27.4	1,650	35	0.80	12,000	0.576	767-200, -300, -200ER
GE90-B4	General Electric	87,400	8.40	39.3	3,037	35	0.80	17,500	—	777
GEnx	General Electric	53,000– 75,000	10	42	—	—	0.85	—	—	787, 747-8
JT8D-15A	Pratt & Whitney	15,500	1.04	16.6	327	30	0.80	4,920	0.779	727, 737, DC9
JT9D-59A	Pratt & Whitney	53,000	4.90	24.5	1,639	35	0.85	11,950	0.646	DC1O-40, A300B, 747-200
PW2037	Pratt & Whitney	38,250	6.00	27.6	1,210	35	0.85	6,500	0.582	757-200
PW4052	Pratt & Whitney	52,000	5.00	27.5	1,700	—	—	—	—	767, A310-300
PW4084	Pratt & Whitney	87,900	6.41	34.4	2,550	35	0.83	—	—	777
CFM56-3C	CFM International	23,500	6.00	22.6	655	35	0.80	5,540	0.648	737-300, -400, -500
CFM56-5C	CFM International	31,200	6.60	31.5	1,027	35	0.80	6,600	0.545	A340

(continued)

Table B.3 Data for some military gas turbine engines (continued)

		Takeoff				Cruise				
Model no.	Manufacturer	Thrust, lbf	BR[a]	OPR[b]	Airflow, lbm/s	Alt, kft	Mach	Thrust, lbf	TSFC[c]	Application
AE 3007	Rolls-Royce	8,600	4.8	20	——	——	——	——	——	Embraer 37, Global Hawk UAV
RB211-524B	Rolls-Royce	50,000	4.50	28.4	1,513	35	0.85	11,000	0.643	L1011-200, 747-200
RB211-535E	Rolls-Royce	40,100	4.30	25.8	1,151	35	0.80	8,495	0.607	757-200
RB211-882	Rolls-Royce	84,700	6.01	39.0	2,640	35	0.83	16,200	0.557	777
Trent 900	Rolls-Royce	70,000–76,500	8.7–8.5	——	2,655–2,745	——	——	——	——	A380
Trent 1000	Rolls-Royce	53,000–75,000	10–11	——	2,400–2,670	——	——	——	——	787
V2528-D5	International Aero Engines	28,000	4.70	30.5	825	35	0.80	5,773	0.574	MD-90
ALF502R-5	Honeywell	6,970	5.70	12.2	——	25	0.70	2,250	0.720	BAe 146-200, –200
TFE731-5	Honeywell	4,500	3.34	14.4	140	40	0.80	986	0.771	BAe 125-800
PW300	Pratt & Whitney Canada	4,750	4.50	23.0	180	40	0.80	1,113	0.675	BAe 1000
FJ44	Williams Rolls	1,900	3.28	12.8	63.3	30	0.70	600	0.750	——
Olympus 593	Rolls-Royce/SNECMA	38,000	0	11.3[d]	410	53	2.00	10,030	1.190	Concorde
GP7270	Engine Alliance	70,000	8.7[d]	45.6[e]	——	35	0.85	12,633	——	A380

[a]BR = bypass ratio. [b]OPR = overall pressure ratio. [c]TSFC = thrust specific fuel consumption. [d]At cruise. [e]max climb.
(Sources: Manufacturers' literature).

Table B.4 Temperature/pressure data for some engines

Temperature and pressure	Pegasus turbofan, separate exhaust	J57 turbojet w/AB exhaust	JT3D turbofan, separate exhaust	JT8D turbofan, mixed exhaust	JT9D turbofan, separate exhaust	F100-PW-100 turbofan, mixed w/AB exhaust
P_{t2}, psia	14.7	14.7	14.7	14.7	14.7	13.1
T_{t2}, °F	59	59	59	59	59	59
$P_{t2.5}$, psia	36.1	54	63	60	32.1	39.3
$T_{t2.5}$, °F	242	330	360	355	210	297
P_{t13}, psia	36.5	—	26	28	22.6	39.3
T_{t13}, °F	257	—	170	190	130	297
P_{t3}, psia	216.9	167	200	233	316	316
T_{t3}, °F	708	660	715	800	880	1,014
P_{t4}, psia	—	158	190	220	302	304
T_{t4}, °F	1,028	1,570	1,600	1,720	1,970	2,566
P_{t5} or P_{t6}, psia	29.3	36	—	2	20.9	38.0
T_{t5} or T_{t6}, °F	510	1,013	—	—	850	1,368
P_{t16}, psia	—	—	—	—	—	36.8
T_{t16}, °F	—	—	—	—	—	303
P_{t6A}, psia	—	—	—	29	—	37.5
T_{t6A}, °F	—	—	—	890	—	960
P_{t7}, psia	—	31.9	28	29	20.9	33.8
T_{t7}, °F	—	2,540	890	890	850	3,204
P_{t17}, psia	36.5	—	26	—	22.4	—
T_{t17}, °F	257	—	170	—	130	—
Bypass ratio α	1.4	0	1.36	1.1	5.0	0.69
Thrust, lbf	21,500	16,000	18,000	14,000	43,500	23,700
Airflow, lbm/s	444	167	460	315	1,495	224

Appendix C
Data for Some Liquid-Propellant Rocket Engines

Table C.1 Data for some liquid-propellant rocket engines

Engine[a]	Thrust (lbf) in vacuum	Expansion ratio ($\varepsilon = A_e/A_t$)	Design alt. (ft) ($P_e = P_a$)	I_{sp} (s) Vacuum	SL	Application
LR-87-BC-13	16,000	45:1	60,000	293	—	Agena
LR-87-AJ-9	474,000	8:1	20,000	283	257	Titan 2—1st stage Titan 3—2d stage Titan Gemini—1st stage
LR-87-AJ-11	548,000	15:1	—	301		Titan 4—lst stage
LR-91-AJ-7	100,570	49:1	100,000	309	—	Titan 2—2d stage Titan 3A-Gemini Titan 3C—3d stage
LR-91-AJ-11	105,000	49.2:1	—	316	—	Titan 4—2d stage
LR-105*	83,700	24.9:1	100,000	304	212	Std. launch vehicle
F-1*	1,726,000	24.9:1	80,000	305	265	Saturn V—1st stage
H-1*	219,000	8:1	80,000	287	255	Saturn 1B
J-2*	200,000	25.5:1	100,000	426	380	Saturn V—2nd and 3d stages
RS-27*	231,700	8:1	—	—	263	Delta launch vehicle

(continued)

Table C.1 Data for some liquid-propellant rocket engines (continued)

Engine[a]	Thrust (lbf) in vacuum	Expansion ratio ($\varepsilon = A_e/A_t$)	Design alt. (ft) ($P_e = P_a$)	I_{sp} (s) Vacuum	I_{sp} (s) SL	Application
SSME*	470,000	77:1	44,600	455	364	Space shuttle main engine
STME*	650,000	45:1	—	428	364	Space transportation main engine
RL10A-4†	20,800	—	—	449	—	Atlas IIA upper stage
HM78†	14,300	83:1	—	446	—	Ariane 5 upper stage
RD-0110‡	30,400	82:1	—	326	—	Soyuz stage 2
RD-180¶	860,200(SL)	36:1	—	338	311	Atlas V
Vulcain 2	286,000	59:1	—	431	—	Ariane 5

[a]Manufacturers: BC = Bell Aerosystems Co.; AJ = Aerojet. * = Rocketdyne. ¶ = Pratt & Whitney. † = Snecma. ‡ = Russia.

Appendix D
Air and $(CH_2)_n$ Properties at Low Pressure

Table D.1 Système International (SI) units

T		f = 0		f = 0.0169		f = 0.0338		f = 0.0507		f = 0.0676	
K	°C	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r
170	−103	169.80	0.1903	170.82	0.1870	171.81	0.1840	172.76	0.1810	173.69	0.1783
180	−93	179.85	0.2324	180.95	0.2288	182.01	0.2254	183.04	0.2221	184.03	0.2190
190	−83	189.90	0.2809	191.08	0.2769	192.22	0.2731	193.33	0.2695	194.40	0.2661
200	−73	199.93	0.3361	201.21	0.3318	202.44	0.3278	203.63	0.3239	204.79	0.3202
210	−63	209.96	0.3985	211.34	0.3941	212.66	0.3899	213.95	0.3859	215.19	0.3821
220	−53	219.99	0.4688	221.47	0.4644	222.89	0.4602	224.28	0.4561	225.62	0.4522
230	−43	230.01	0.5475	231.60	0.5433	233.13	0.5392	234.62	0.5352	236.06	0.5315
240	−33	240.02	0.6352	241.73	0.6313	243.38	0.6276	244.98	0.6240	246.53	0.6205
250	−23	250.04	0.7325	251.87	0.7292	253.64	0.7260	255.36	0.7230	257.02	0.7201
260	−13	260.05	0.8399	262.01	0.8376	263.91	0.8353	265.75	0.8331	267.53	0.8310
270	−3	270.07	0.9581	272.17	0.9571	274.19	0.9561	276.16	0.9551	278.06	0.9542
280	7	280.08	1.0878	282.32	1.0885	284.49	1.0891	286.58	1.0898	288.61	1.0904
290	17	290.10	1.2296	292.49	1.2325	294.79	1.2352	297.03	1.2379	299.19	1.2406
300	27	300.13	1.3841	302.66	1.3897	305.11	1.3952	307.49	1.4005	309.79	1.4056
310	37	310.15	1.5521	312.85	1.5611	315.45	1.5699	317.97	1.5783	320.41	1.5865

(continued)

Table D.1 Système International (SI) units (continued)

T		$f = 0$		$f = 0.0169$		$f = 0.0338$		$f = 0.0507$		$f = 0.0676$	
K	°C	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r
320	47	320.19	1.7344	323.04	1.7474	325.80	1.7601	328.47	1.7724	331.05	1.7844
330	57	330.23	1.9315	333.25	1.9494	336.16	1.9667	338.99	1.9836	341.72	2.00
340	67	340.28	2.14	343.47	2.17	346.55	2.19	349.53	2.21	352.42	2.23
350	77	350.34	2.37	353.70	2.40	356.95	2.43	360.09	2.46	363.13	2.49
360	87	360.41	2.62	363.94	2.66	367.36	2.69	370.67	2.73	373.88	2.77
370	97	370.49	2.88	374.20	2.93	377.80	2.98	381.27	3.02	384.64	3.06
380	107	380.58	3.17	384.48	3.22	388.25	3.28	391.90	3.33	395.44	3.39
390	117	390.68	3.47	394.77	3.54	398.72	3.61	402.55	3.67	406.26	3.74
400	127	400.80	3.80	405.08	3.88	409.22	3.95	413.22	4.03	417.10	4.11
410	137	410.93	4.14	415.40	4.24	419.73	4.33	423.92	4.42	427.98	4.51
420	147	421.07	4.51	425.74	4.62	430.26	4.73	434.64	4.84	438.88	4.94
430	157	431.23	4.90	436.10	5.03	440.82	5.16	445.38	5.28	449.80	5.40
440	167	441.41	5.32	446.49	5.47	451.40	5.61	456.15	5.76	460.76	5.90
450	177	451.60	5.76	456.89	5.93	462.00	6.10	466.95	6.26	471.74	6.43
460	187	461.81	6.23	467.31	6.42	472.62	6.61	477.77	6.80	482.75	6.99
470	197	472.04	6.72	477.75	6.94	483.27	7.16	488.62	7.38	493.79	7.59
480	207	482.28	7.25	488.21	7.50	493.94	7.74	499.49	7.99	504.86	8.23
490	217	492.55	7.80	498.69	8.08	504.63	8.36	510.39	8.64	515.96	8.92
500	227	502.83	8.39	509.20	8.70	515.35	9.02	521.31	9.33	527.09	9.64
510	237	513.13	9.01	519.72	9.36	526.10	9.71	532.27	10.06	538.24	10.41
520	247	523.46	9.66	530.27	10.05	536.87	10.44	543.25	10.83	549.43	11.23
530	257	533.80	10.35	540.85	10.78	547.66	11.22	554.26	11.65	560.65	12.09
540	267	544.17	11.07	551.44	11.55	558.48	12.03	565.30	12.52	571.89	13.01
550	277	554.55	11.83	562.06	12.36	569.33	12.90	576.36	13.44	583.17	13.98

560	287	564.96	12.63	572.71	13.21	580.20	13.81	587.46	14.41	594.48	15.01
570	297	575.39	13.47	583.38	14.11	591.10	14.77	598.58	15.43	605.82	16.09
580	307	585.84	14.35	594.07	15.06	602.03	15.78	609.73	16.50	617.19	17.24
590	317	596.32	15.27	604.79	16.05	612.98	16.84	620.91	17.64	628.59	18.45
600	327	606.81	16.24	615.53	17.09	623.96	17.96	632.12	18.83	640.02	19.72
600	327	606.81	16.24	615.53	17.09	623.96	17.96	632.12	18.83	640.02	19.72
610	337	617.33	17.25	626.30	18.18	634.97	19.13	643.36	20.09	651.49	21.06
620	347	627.88	18.32	637.09	19.33	646.00	20.36	654.63	21.41	662.98	22.48
630	357	638.44	19.43	647.91	20.53	657.07	21.66	665.93	22.80	674.51	23.97
640	367	649.03	20.59	658.75	21.79	668.16	23.01	677.25	24.26	686.07	25.53
650	377	659.65	21.80	669.62	23.11	679.27	24.44	688.61	25.79	697.65	27.18
660	387	670.29	23.07	680.52	24.48	690.42	25.93	700.00	27.40	709.28	28.91
670	397	680.95	24.40	691.44	25.93	701.59	27.49	711.42	29.09	720.93	30.72
680	407	691.63	25.78	702.39	27.43	712.79	29.12	722.86	30.86	732.61	32.63
690	417	702.34	27.23	713.36	29.01	724.02	30.83	734.34	32.71	744.33	34.63
700	427	713.07	28.73	724.36	30.65	735.28	32.62	745.84	34.65	756.08	36.72
710	437	723.83	30.30	735.38	32.36	746.56	34.49	757.38	36.68	767.85	38.92
720	447	734.61	31.93	746.43	34.15	757.87	36.44	768.94	38.80	779.67	41.22
730	457	745.41	33.64	757.51	36.02	769.21	38.48	780.54	41.02	791.51	43.63
740	467	756.24	35.41	768.61	37.97	780.58	40.61	792.16	43.34	803.38	46.15
750	477	767.09	37.25	779.74	39.99	791.98	42.83	803.82	45.76	815.29	48.79
760	487	777.97	39.17	790.90	42.10	803.40	45.15	815.50	48.29	827.22	51.54
770	497	788.87	41.16	802.08	44.30	814.85	47.56	827.22	50.94	839.19	54.42
780	507	799.79	43.23	813.28	46.59	826.33	50.08	838.96	53.69	851.19	57.43
790	517	810.74	45.39	824.51	48.97	837.83	52.70	850.73	56.57	863.21	60.58
800	527	821.71	47.62	835.77	51.45	849.37	55.43	862.53	59.57	875.27	63.86
810	537	832.70	49.94	847.05	54.02	860.93	58.27	874.36	62.69	887.36	67.28

(continued)

Table D.1 Système International (SI) units (continued)

T		$f = 0$		$f = 0.0169$		$f = 0.0338$		$f = 0.0507$		$f = 0.0676$	
K	°C	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r
820	547	843.72	52.35	858.35	56.69	872.51	61.22	886.22	65.94	899.48	70.85
830	557	854.76	54.85	869.69	59.47	884.13	64.30	898.10	69.33	911.64	74.57
840	567	865.82	57.44	881.04	62.36	895.77	67.50	910.02	72.86	923.82	78.45
850	577	876.90	60.13	892.42	65.35	907.43	70.82	921.96	76.53	936.03	82.49
860	587	888.01	62.91	903.83	68.46	919.12	74.27	933.93	80.35	948.27	86.70
870	597	899.14	65.80	915.26	71.68	930.84	77.86	945.93	84.33	960.54	91.09
880	607	910.29	68.79	926.71	75.02	942.59	81.58	957.96	88.46	972.84	95.65
890	617	921.47	71.88	938.19	78.49	954.36	85.44	970.01	92.75	985.17	100.40
900	627	932.66	75.08	949.69	82.08	966.15	89.46	982.09	97.21	997.52	105.33
910	637	943.88	78.40	961.21	85.80	977.97	93.62	994.20	101.84	1009.91	110.46
920	647	955.12	81.82	972.76	89.66	989.82	97.93	1006.33	106.64	1022.32	115.80
930	657	966.38	85.37	984.33	93.65	1001.69	102.40	1018.49	111.64	1034.77	121.34
940	667	977.66	89.03	995.92	97.78	1013.58	107.04	1030.68	116.81	1047.24	127.10
950	677	988.96	92.82	1007.54	102.06	1025.50	111.84	1042.89	122.19	1059.73	133.09
960	687	1000.28	96.74	1019.17	106.48	1037.45	116.82	1055.13	127.76	1072.26	139.29
970	697	1011.62	100.78	1030.83	111.06	1049.41	121.97	1067.40	133.53	1084.81	145.74
980	707	1022.99	104.96	1042.51	115.79	1061.41	127.31	1079.69	139.52	1097.39	152.43
990	717	1034.37	109.27	1054.22	120.68	1073.42	132.83	1092.00	145.72	1110.00	159.36
1000	727	1045.77	113.72	1065.94	125.74	1085.46	138.54	1104.34	152.14	1122.63	166.55
1000	727	1045.77	113.72	1065.94	125.74	1085.46	138.54	1104.34	152.14	1122.63	166.55
1010	737	1057.19	118.31	1077.69	130.96	1097.52	144.45	1116.71	158.79	1135.29	174.01
1020	747	1068.63	123.05	1089.45	136.36	1109.60	150.56	1129.09	165.68	1147.97	181.74
1030	757	1080.09	127.94	1101.24	141.93	1121.70	156.88	1141.51	172.81	1160.68	189.74
1040	767	1091.56	132.98	1113.05	147.68	1133.83	163.41	1153.94	180.19	1173.42	198.03

1050	777	1103.06	138.18	1124.87	153.62	1145.98	170.15	1166.40	187.82	1186.18	206.6
1060	787	1114.57	143.53	1136.72	159.74	1158.15	177.13	1178.89	195.71	1198.97	215.5
1070	797	1126.10	149.05	1148.59	166.06	1170.34	184.32	1191.39	203.9	1211.78	224.7
1080	807	1137.65	154.73	1160.47	172.58	1182.55	191.76	1203.92	212.3	1224.61	234.2
1090	817	1149.22	160.59	1172.38	179.30	1194.78	199.43	1216.47	221.0	1237.47	244.1
1100	827	1160.80	166.62	1184.30	186.23	1207.04	207.4	1229.04	230.0	1250.35	254.3
1110	837	1172.40	172.83	1196.24	193.38	1219.31	215.5	1241.64	239.3	1263.26	264.8
1120	847	1184.01	179.22	1208.21	200.7	1231.61	224.0	1254.25	248.9	1276.18	275.7
1130	857	1195.65	185.79	1220.18	208.3	1243.92	232.7	1266.89	258.9	1289.13	287.0
1140	867	1207.29	192.55	1232.18	216.1	1256.25	241.6	1279.55	269.1	1302.11	298.6
1150	877	1218.96	199.51	1244.19	224.2	1268.60	250.9	1292.23	279.7	1315.10	310.6
1160	887	1230.64	206.7	1256.22	232.4	1280.97	260.4	1304.93	290.6	1328.12	323.0
1170	897	1242.33	214.0	1268.27	241.0	1293.36	270.2	1317.65	301.8	1341.16	335.9
1180	907	1254.05	221.6	1280.34	249.8	1305.77	280.3	1330.39	313.4	1354.22	349.1
1190	917	1265.77	229.4	1292.42	258.8	1318.20	290.8	1343.15	325.4	1367.30	362.8
1200	927	1277.51	237.4	1304.52	268.1	1330.64	301.5	1355.92	337.7	1380.41	376.8
1210	937	1289.27	245.6	1316.63	277.6	1343.10	312.5	1368.72	350.4	1393.53	391.4
1220	947	1301.03	254.0	1328.76	287.4	1355.58	323.9	1381.54	363.5	1406.68	406.4
1230	957	1312.82	262.6	1340.91	297.5	1368.08	335.6	1394.38	377.0	1419.84	421.9
1240	967	1324.61	271.5	1353.07	307.9	1380.59	347.7	1407.23	390.9	1433.02	437.8
1250	977	1336.43	280.6	1365.24	318.6	1393.12	360.1	1420.10	405.2	1446.23	454.3
1260	987	1348.25	290.0	1377.44	329.6	1405.67	372.8	1432.99	420.0	1459.45	471.2
1270	997	1360.09	299.6	1389.64	340.8	1418.23	385.9	1445.90	435.2	1472.69	488.7
1280	1007	1371.94	309.5	1401.86	352.4	1430.81	399.4	1458.83	450.8	1485.96	506.7
1290	1017	1383.80	319.6	1414.10	364.3	1443.41	413.3	1471.77	466.8	1499.24	525.2
1300	1027	1395.68	330.0	1426.35	376.5	1456.02	427.5	1484.73	483.4	1512.54	544.3
1310	1037	1407.57	340.6	1438.61	389.0	1468.64	442.2	1497.71	500.4	1525.85	564.0

(continued)

Table D.1 Système International (SI) units (continued)

T		$f=0$		$f=0.0169$		$f=0.0338$		$f=0.0507$		$f=0.0676$	
K	°C	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r
1320	1047	1419.47	351.6	1450.89	401.8	1481.29	457.2	1510.70	517.9	1539.19	584.2
1330	1057	1431.38	362.7	1463.18	415.0	1493.94	472.6	1523.71	535.9	1552.54	605.0
1340	1067	1443.31	374.2	1475.49	428.6	1506.61	488.5	1536.74	554.4	1565.91	626.5
1350	1077	1455.25	386.0	1487.81	442.5	1519.30	504.8	1549.78	573.4	1579.30	648.5
1360	1087	1467.20	398.0	1500.14	456.7	1532.00	521.6	1562.84	593.0	1592.70	671.2
1370	1097	1479.16	410.3	1512.48	471.3	1544.72	538.8	1575.92	613.1	1606.13	694.6
1380	1107	1491.13	423.0	1524.84	486.3	1557.45	556.4	1589.01	633.7	1619.57	718.6
1390	1117	1503.11	435.9	1537.21	501.7	1570.19	574.5	1602.11	654.9	1633.02	743.3
1400	1127	1515.11	449.2	1549.59	517.4	1582.95	593.1	1615.23	676.7	1646.49	768.6
1400	1127	1515.11	449.2	1549.59	517.4	1582.95	593.1	1615.23	676.7	1646.49	768.6
1410	1137	1527.11	462.8	1561.99	533.6	1595.72	612.2	1628.37	699.1	1659.98	794.7
1420	1147	1539.13	476.7	1574.39	550.1	1608.51	631.7	1641.52	722.0	1673.49	821.5
1430	1157	1551.16	490.9	1586.81	567.1	1621.30	651.8	1654.68	745.6	1687.01	849.1
1440	1167	1563.20	505.4	1599.25	584.4	1634.12	672.4	1667.86	769.8	1700.54	877.4
1450	1177	1575.25	520.4	1611.69	602.2	1646.94	693.4	1681.06	794.6	1714.09	906.5
1460	1187	1587.31	535.6	1624.14	620.4	1659.78	715.1	1694.27	820.2	1727.66	936.4
1470	1197	1599.38	551.2	1636.61	639.1	1672.63	737.2	1707.49	846.3	1741.24	967.0
1480	1207	1611.46	567.2	1649.09	658.2	1685.49	760.0	1720.72	873.1	1754.84	998.5
1490	1217	1623.55	583.5	1661.58	677.8	1698.37	783.2	1733.97	900.7	1768.45	1030.8
1500	1227	1635.65	600.2	1674.08	697.8	1711.26	807.1	1747.24	928.9	1782.08	1064.0
1510	1237	1647.76	617.2	1686.59	718.3	1724.16	831.5	1760.51	957.8	1795.72	1098.1
1520	1247	1659.88	634.7	1699.11	739.3	1737.07	856.6	1773.80	987.5	1809.38	1133.1
1530	1257	1672.01	652.5	1711.65	760.7	1749.99	882.2	1787.11	1018.0	1823.05	1168.9
1540	1267	1684.15	670.7	1724.19	782.7	1762.93	908.5	1800.42	1049.1	1836.73	1205.7

1550	1277	1696.29	689.4	1736.75	805.2	1775.88	935.4	1813.75	1081.1	1850.43	1243.5
1560	1287	1708.45	708.4	1749.31	828.2	1788.84	962.9	1827.10	1113.9	1864.14	1282.2
1570	1297	1720.62	727.9	1761.89	851.6	1801.81	991.1	1840.45	1147.4	1877.86	1321.9
1580	1307	1732.80	747.7	1774.48	875.7	1814.80	1019.9	1853.82	1181.8	1891.60	1362.6
1590	1317	1744.98	768.0	1787.08	900.3	1827.79	1049.5	1867.20	1217.0	1905.36	1404.3
1600	1327	1757.18	788.8	1799.68	925.4	1840.80	1079.7	1880.59	1253.1	1919.12	1447.1
1610	1337	1769.38	810.0	1812.30	951.1	1853.81	1110.6	1893.99	1290.0	1932.90	1490.9
1620	1347	1781.59	831.6	1824.93	977.3	1866.84	1142.2	1907.41	1327.8	1946.69	1535.9
1630	1357	1793.82	853.7	1837.56	1004.2	1879.88	1174.6	1920.84	1366.6	1960.50	1581.9
1640	1367	1806.05	876.2	1850.21	1031.6	1892.93	1207.6	1934.28	1406.2	1974.31	1629.1
1650	1377	1818.29	899.2	1862.87	1059.6	1905.99	1241.5	1947.73	1446.8	1988.15	1677.4
1660	1387	1830.54	922.7	1875.54	1088.2	1919.06	1276.1	1961.19	1488.3	2001.99	1726.9
1670	1397	1842.79	946.7	1888.21	1117.4	1932.15	1311.5	1974.67	1530.8	2015.84	1777.6
1680	1407	1855.06	971.2	1900.90	1147.3	1945.24	1347.6	1988.15	1574.3	2029.71	1829.5
1690	1417	1867.33	996.1	1913.59	1177.8	1958.34	1384.6	2001.65	1618.8	2043.59	1882.6
1700	1427	1879.61	1021.6	1926.30	1209.0	1971.45	1422.4	2015.16	1664.3	2057.48	1937.0
1710	1437	1891.90	1047.6	1939.01	1240.8	1984.58	1461.0	2028.68	1710.8	2071.38	1992.8
1720	1447	1904.20	1074.1	1951.73	1273.2	1997.71	1500.5	2042.21	1758.4	2085.30	2049.8
1730	1457	1916.51	1101.1	1964.46	1306.4	2010.85	1540.8	2055.75	1807.1	2099.23	2108.1
1740	1467	1928.82	1128.7	1977.20	1340.2	2024.01	1582.0	2069.30	1856.9	2113.16	2167.8
1750	1477	1941.14	1156.8	1989.95	1374.8	2037.17	1624.1	2082.86	1907.8	2127.11	2229
1760	1487	1953.47	1185.5	2002.71	1410.0	2050.34	1667.1	2096.44	1959.8	2141.07	2291
1770	1497	1965.81	1214.7	2015.48	1446.0	2063.52	1711.0	2110.02	2013.0	2155.05	2355
1780	1507	1978.16	1244.5	2028.25	1482.7	2076.71	1755.8	2123.61	2067.3	2169.03	2421
1790	1517	1990.51	1274.9	2041.04	1520.1	2089.91	1801.6	2137.22	2122.8	2183.02	2488
1800	1527	2002.87	1305.8	2053.83	1558.3	2103.12	1848.3	2150.83	2179.6	2197.03	2556
1810	1537	2015.24	1337.4	2066.63	1597.3	2116.34	1896.0	2164.45	2238	2211.04	2626

(continued)

Table D.1 Système International (SI) units (continued)

T		$f=0$		$f=0.0169$		$f=0.0338$		$f=0.0507$		$f=0.0676$	
K	°C	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r	h, kJ/kg	P_r
1820	1547	2027.61	1369.5	2079.44	1637.0	2129.57	1944.8	2178.08	2297	2225.07	2697
1830	1557	2040.00	1402.3	2092.25	1677.6	2142.80	1994.5	2191.73	2357	2239.10	2771
1840	1567	2052.39	1435.7	2105.08	1718.9	2156.05	2045.2	2205.38	2419	2253.15	2845
1850	1577	2064.78	1469.7	2117.91	1761.0	2169.30	2097	2219.04	2482	2267.20	2922
1860	1587	2077.19	1504.3	2130.75	1804.0	2182.56	2150	2232.71	2547	2281.27	3000
1870	1597	2089.60	1539.6	2143.60	1847.8	2195.83	2204	2246.39	2613	2295.34	3080
1880	1607	2102.02	1575.6	2156.45	1892.4	2209.11	2259	2260.08	2680	2309.43	3161
1890	1617	2114.44	1612.2	2169.32	1938.0	2222.40	2315	2273.77	2748	2323.52	3244
1900	1627	2126.87	1649.4	2182.19	1984.3	2235.69	2372	2287.48	2818	2337.63	3329
1910	1637	2139.31	1687.4	2195.06	2031.6	2249.00	2430	2301.19	2890	2351.74	3416
1920	1647	2151.75	1726.0	2207.95	2079.8	2262.31	2490	2314.92	2963	2365.86	3505
1930	1657	2164.20	1765.4	2220.84	2128.8	2275.62	2551	2328.65	3037	2379.99	3595
1940	1667	2176.66	1805.4	2233.74	2178.8	2288.95	2612	2342.39	3113	2394.13	3688
1950	1677	2189.12	1846.2	2246.64	2230	2302.28	2676	2356.13	3191	2408.28	3782
1960	1687	2201.59	1887.7	2259.55	2282	2315.62	2740	2369.89	3270	2422.43	3879
1970	1697	2214.06	1929.9	2272.47	2334	2328.97	2805	2383.65	3350	2436.60	3977
1980	1707	2226.54	1972.8	2285.40	2388	2342.32	2872	2397.42	3433	2450.77	4078
1990	1717	2239.03	2016.6	2298.33	2443	2355.68	2940	2411.20	3516	2464.95	4180
2000	1727	2251.52	2061	2311.26	2499	2369.05	3010	2424.98	3602	2479.14	4285
2010	1737	2264.02	2106	2324.21	2556	2382.43	3080	2438.77	3689	2493.34	4392
2020	1747	2276.52	2152	2337.16	2614	2395.81	3152	2452.57	3778	2507.54	4501
2030	1757	2289.03	2199	2350.11	2672	2409.20	3226	2466.38	3869	2521.75	4612
2040	1767	2301.55	2247	2363.07	2732	2422.59	3301	2480.19	3961	2535.97	4725
2050	1777	2314.07	2295	2376.04	2793	2435.99	3377	2494.01	4055	2550.20	4841

2060	1787	2326.59	2345	2389.01	2855	2449.40	3454	2507.84	4152	2564.43	4959
2070	1797	2339.12	2395	2401.99	2919	2462.81	3533	2521.67	4249	2578.67	5079
2080	1807	2351.65	2446	2414.98	2983	2476.23	3614	2535.52	4349	2592.92	5202
2090	1817	2364.19	2497	2427.97	3048	2489.66	3696	2549.36	4451	2607.18	5327
2100	1827	2376.74	2550	2440.96	3115	2503.09	3779	2563.22	4554	2621.44	5455
2110	1837	2389.29	2604	2453.97	3183	2516.53	3864	2577.07	4660	2635.71	5585
2120	1847	2401.85	2658	2466.97	3252	2529.97	3950	2590.94	4767	2649.98	5717
2130	1857	2414.41	2713	2479.98	3322	2543.42	4038	2604.81	4877	2664.26	5853
2140	1867	2426.97	2769	2493.00	3393	2556.88	4128	2618.69	4988	2678.55	5990
2150	1877	2439.54	2827	2506.03	3465	2570.34	4219	2632.58	5102	2692.85	6131
2160	1887	2452.12	2885	2519.06	3539	2583.80	4312	2646.47	5218	2707.15	6274
2170	1897	2464.70	2944	2532.09	3614	2597.28	4406	2660.37	5336	2721.46	6420
2180	1907	2477.29	3004	2545.13	3690	2610.76	4502	2674.27	5456	2735.77	6568
2190	1917	2489.88	3065	2558.18	3768	2624.24	4600	2688.18	5578	2750.10	6720
2200	1927	2502.48	3126	2571.23	3847	2637.73	4699	2702.10	5702	2764.43	6874
2210	1937	2515.08	3189	2584.29	3927	2651.23	4801	2716.02	5829	2778.76	7031
2220	1947	2527.69	3253	2597.35	4008	2664.74	4904	2729.95	5958	2793.11	7191

Table D.2 British Engineering (BE) units

T		$f=0$		$f=0.0169$		$f=0.0338$		$f=0.0507$		$f=0.0676$	
°R	°F	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r
300	−160	71.55	0.1775	71.98	0.1744	72.40	0.1715	72.80	0.1687	73.19	0.1660
320	−140	76.36	0.2225	76.82	0.2190	77.27	0.2156	77.71	0.2124	78.13	0.2094
340	−120	81.16	0.2752	81.66	0.2712	82.15	0.2675	82.62	0.2639	83.08	0.2605
360	−100	85.95	0.3361	86.50	0.3318	87.03	0.3278	87.54	0.3239	88.04	0.3202
380	−80	90.74	0.4059	91.34	0.4015	91.91	0.3973	92.47	0.3933	93.01	0.3894
400	−60	95.53	0.4856	96.18	0.4812	96.80	0.4769	97.40	0.4729	97.99	0.4690
420	−40	100.32	0.5757	101.02	0.5716	101.69	0.5675	102.35	0.5637	102.98	0.5600
440	−20	105.10	0.6772	105.86	0.6736	106.59	0.6700	107.30	0.6667	107.99	0.6634
460	0	109.88	0.7909	110.70	0.7881	111.49	0.7854	112.26	0.7828	113.00	0.7803
480	20	114.67	0.9175	115.55	0.9160	116.40	0.9145	117.23	0.9131	118.03	0.9117
500	40	119.45	1.0580	120.40	1.0582	121.32	1.0585	122.21	1.0587	123.07	1.0589
520	60	124.24	1.213	125.25	1.216	126.24	1.218	127.19	1.221	128.12	1.223
540	80	129.02	1.384	130.11	1.390	131.17	1.395	132.19	1.400	133.18	1.406
560	100	133.81	1.572	134.98	1.581	136.11	1.590	137.20	1.599	138.25	1.608
580	120	138.61	1.777	139.85	1.791	141.05	1.805	142.21	1.818	143.34	1.831
600	140	143.41	2.00	144.73	2.02	146.00	2.04	147.24	2.06	148.44	2.08
620	160	148.21	2.24	149.61	2.27	150.97	2.30	152.28	2.32	153.55	2.35
640	180	153.01	2.51	154.50	2.54	155.94	2.58	159.33	2.61	158.68	2.64
660	200	157.83	2.79	159.40	2.84	160.92	2.88	162.39	2.92	163.81	2.96
680	220	162.65	3.10	164.30	3.16	165.91	3.21	167.46	3.26	168.97	3.31
700	240	167.47	3.44	169.22	3.50	170.91	3.57	172.55	3.63	174.13	3.70
720	260	172.30	3.80	174.14	3.88	175.92	3.95	177.64	4.03	179.31	4.11
740	280	177.14	4.18	179.07	4.28	180.94	4.37	182.75	4.47	184.51	4.56
760	300	181.99	4.59	184.02	4.71	185.98	4.82	187.88	4.93	189.72	5.04

780	320	186.84	5.04	188.97	5.17	191.02	5.30	193.01	5.44	194.94	5.57
800	340	191.71	5.51	193.93	5.67	196.08	5.82	198.16	5.98	200.18	6.13
820	360	196.58	6.02	198.90	6.20	201.15	6.38	203.32	6.56	205.43	6.74
840	380	201.46	6.56	203.89	6.77	206.23	6.97	208.50	7.18	210.70	7.39
860	400	206.35	7.13	208.88	7.37	211.32	7.61	213.69	7.85	215.98	8.09
880	420	211.25	7.74	213.89	8.02	216.43	8.29	218.89	8.57	221.28	8.84
900	440	216.17	8.39	218.90	8.70	221.55	9.02	224.11	9.33	226.59	9.64
920	460	221.09	9.08	223.93	9.43	226.68	9.79	229.35	10.14	231.92	10.50
940	480	226.02	9.81	228.97	10.21	231.83	10.61	234.59	11.01	237.27	11.42
960	500	230.96	10.58	234.03	11.03	236.99	11.48	239.86	11.94	242.63	12.39
980	520	235.92	11.40	239.09	11.91	242.16	12.41	245.13	12.92	248.01	13.44
1000	540	240.89	12.27	244.17	12.83	247.35	13.40	250.43	13.97	253.40	14.54
1020	560	245.86	13.18	249.26	13.81	252.55	14.44	255.73	15.08	258.82	15.72
1040	580	250.85	14.15	254.37	14.84	257.77	15.55	261.06	16.26	264.24	16.98
1060	600	255.86	15.17	259.49	15.94	263.00	16.72	266.39	17.51	269.69	18.31
1080	620	260.87	16.24	264.62	17.09	268.24	17.96	271.75	18.83	275.15	19.72
1100	640	265.89	17.37	269.76	18.31	273.50	19.26	277.12	20.23	280.62	21.22
1100	640	265.89	17.37	269.76	18.31	273.50	19.26	277.12	20.23	280.62	21.22
1120	660	270.93	18.56	274.92	19.59	278.77	20.64	282.50	21.72	286.12	22.80
1140	680	275.98	19.81	280.09	20.94	284.06	22.10	287.90	23.28	291.63	24.48
1160	700	281.05	21.12	285.27	22.37	289.36	23.64	293.32	24.93	297.15	26.25
1180	720	286.12	22.50	290.47	23.86	294.68	25.26	298.75	26.68	302.70	28.13
1200	740	291.21	23.95	295.68	25.44	300.01	26.96	304.20	28.52	308.26	30.11
1220	760	296.31	25.47	300.91	27.09	305.36	28.75	309.66	30.46	313.83	32.20
1240	780	301.42	27.06	306.15	28.83	310.72	30.64	315.14	32.50	319.43	34.40
1260	800	306.55	28.73	311.40	30.65	316.10	32.62	320.64	34.65	325.04	36.72
1280	820	311.69	30.48	316.67	32.56	321.49	34.70	326.15	36.91	330.66	39.17

(continued)

Table D.2 British Engineering (BE) units (continued)

T		$f = 0$		$f = 0.0169$		$f = 0.0338$		$f = 0.0507$		$f = 0.0676$	
°R	°F	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r
1300	840	316.84	32.31	321.95	34.56	326.89	36.89	331.68	39.28	336.31	41.75
1320	860	322.00	34.22	327.24	36.66	332.31	39.18	337.22	41.78	341.97	44.46
1340	880	327.18	36.22	332.55	38.86	337.75	41.59	342.78	44.40	347.65	47.31
1360	900	332.37	38.28	337.87	41.16	343.20	44.11	348.35	47.16	353.34	50.30
1380	920	337.57	40.49	343.21	43.64	348.66	46.95	353.94	50.39	359.05	53.95
1400	940	342.79	42.77	348.56	46.07	354.14	49.51	359.54	53.07	364.78	56.75
1420	960	348.01	45.14	353.92	48.70	359.63	52.40	365.17	56.24	370.52	60.22
1440	980	353.25	47.62	359.30	51.45	365.14	55.43	370.80	59.57	376.28	63.86
1460	1000	358.50	50.21	364.69	54.31	370.67	58.59	376.45	63.04	382.06	67.67
1480	1020	363.77	52.90	370.09	57.30	376.20	61.90	382.12	66.69	387.85	71.66
1500	1040	369.04	55.70	375.50	60.42	381.75	65.35	387.80	70.49	393.66	75.85
1520	1060	374.33	58.62	380.93	63.67	387.32	68.96	393.50	74.48	399.48	80.23
1540	1080	379.63	61.66	386.37	67.06	392.90	72.72	399.21	78.64	405.32	84.81
1560	1100	384.95	64.83	391.83	70.59	398.49	76.65	404.93	82.98	411.18	89.61
1580	1120	390.27	68.11	397.30	74.27	404.10	80.74	410.68	87.52	417.05	94.62
1600	1140	395.60	71.53	402.78	78.10	409.72	85.01	416.43	92.26	422.93	99.86
1620	1160	400.95	75.08	408.27	82.08	415.35	89.46	422.20	97.21	428.83	105.33
1640	1180	406.31	78.77	413.78	86.22	421.00	94.09	427.98	102.36	434.75	111.05
1660	1200	411.68	82.60	419.29	90.53	426.66	98.91	433.78	107.74	440.68	117.01
1680	1220	417.06	86.58	424.82	95.01	432.33	103.93	439.60	113.34	446.63	123.24
1700	1240	422.45	90.70	430.36	99.66	438.02	109.15	445.42	119.18	452.59	129.73
1720	1260	427.86	94.98	435.92	104.50	443.72	114.59	451.26	125.26	458.57	136.51
1740	1280	433.27	99.42	441.48	109.52	449.43	120.23	457.12	131.58	464.56	143.56
1760	1300	438.70	104.02	447.06	114.73	455.15	126.11	462.98	138.17	470.57	150.92

1780	1320	444.13	108.78	452.65	120.13	460.89	132.21	468.86	145.02	476.59	158.58
1800	1340	449.58	113.72	458.25	125.74	466.64	138.54	474.76	152.14	482.62	166.55
1820	1360	455.03	118.83	463.86	131.55	472.40	145.12	480.66	159.55	488.67	174.85
1840	1380	460.50	124.13	469.48	137.58	478.17	151.95	486.58	167.24	494.73	183.49
1860	1400	465.97	129.60	475.11	143.82	483.96	159.03	492.51	175.24	500.80	192.47
1880	1420	471.46	135.27	480.76	150.29	489.75	166.38	498.46	183.55	506.89	201.8
1900	1440	476.95	141.13	486.41	157.00	495.56	174.00	504.42	192.17	512.99	211.5
1900	1440	476.95	141.13	486.41	157.00	495.56	174.00	504.42	192.17	512.99	211.5
1920	1460	482.46	147.19	492.08	163.93	501.38	181.90	510.39	201.1	519.11	221.6
1940	1480	487.97	153.46	497.75	171.11	507.21	191.09	516.37	210.4	525.23	232.1
1960	1500	493.50	159.93	503.44	178.55	513.05	198.57	522.36	220.0	531.37	243.0
1980	1520	499.03	166.62	509.13	186.23	518.91	207.4	528.37	230.0	537.53	254.3
2000	1540	504.57	173.53	514.84	194.2	524.77	216.4	534.38	240.4	543.69	266.0
2020	1560	510.12	180.66	520.55	202.4	530.64	225.9	540.41	251.1	549.87	278.2
2040	1580	515.68	188.02	526.28	210.9	536.53	235.6	546.45	262.2	556.06	290.8
2060	1600	521.24	195.62	532.01	219.7	542.42	245.7	552.50	273.8	562.26	303.9
2080	1620	526.82	203.5	537.75	228.7	548.33	256.1	558.56	285.7	568.47	317.5
2100	1640	532.40	211.6	543.50	238.1	554.24	266.9	564.63	298.0	574.70	331.5
2120	1660	537.99	219.9	549.26	247.8	560.16	278.1	570.72	310.8	580.93	346.1
2140	1680	543.59	228.5	555.03	257.8	566.10	289.6	576.81	324.0	587.18	361.2
2160	1700	549.20	237.4	560.81	268.1	572.04	301.5	582.91	337.7	593.44	376.8
2180	1720	554.82	246.5	566.60	278.7	578.00	313.8	589.03	351.9	599.71	393.0
2200	1740	560.44	255.9	572.39	289.7	583.96	326.5	595.15	366.5	605.99	409.8
2220	1760	566.07	265.6	578.20	301.0	589.93	339.6	601.28	381.6	612.28	427.1
2240	1780	571.71	275.6	584.01	312.6	595.91	353.1	607.43	397.2	618.58	445.1
2260	1800	577.35	285.8	589.83	324.6	601.90	367.1	613.58	413.4	624.89	463.6
2280	1820	583.00	296.4	595.66	337.0	607.90	381.5	619.74	430.0	631.21	482.8

(continued)

Table D.2 British Engineering (BE) units (continued)

T		$f = 0$		$f = 0.0169$		$f = 0.0338$		$f = 0.0507$		$f = 0.0676$	
°R	°F	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r
2300	1840	588.66	307.3	601.49	349.8	613.90	396.4	625.91	447.3	637.54	502.6
2320	1860	594.33	318.5	607.34	362.9	619.92	411.7	632.10	465.0	643.89	523.1
2340	1880	600.00	330.0	613.19	376.5	625.94	427.5	638.29	483.4	650.24	544.3
2360	1900	605.68	341.8	619.05	390.4	631.97	443.8	644.49	502.3	656.60	566.2
2380	1920	611.37	354.0	624.91	404.7	638.01	460.6	650.69	521.8	662.97	588.8
2400	1940	617.06	366.5	630.78	419.5	644.06	477.9	656.91	542.0	669.35	612.1
2420	1960	622.76	379.4	636.66	434.7	650.12	495.7	663.14	562.8	675.74	636.2
2440	1980	628.46	392.6	642.55	450.3	656.18	514.1	669.37	584.2	682.14	661.1
2460	2000	634.17	406.2	648.45	466.4	662.25	533.0	675.61	606.3	688.55	686.7
2480	2020	639.89	420.2	654.35	482.9	668.33	552.4	681.86	629.1	694.97	713.2
2500	2040	645.62	434.5	660.26	499.9	674.42	572.5	688.12	652.5	701.39	740.5
2520	2060	651.34	449.2	666.17	517.4	680.51	593.1	694.39	676.7	707.83	768.6
2540	2080	657.08	464.3	672.09	535.4	686.61	614.3	700.66	711.6	714.27	797.7
2560	2100	662.82	479.8	678.02	553.8	692.72	636.1	706.95	727.2	720.72	827.6
2580	2120	668.57	495.7	683.95	572.8	698.83	658.6	713.24	753.6	727.18	858.4
2600	2140	674.32	512.0	689.89	592.3	704.96	681.7	719.53	780.8	733.65	890.2
2620	2160	680.08	528.8	695.84	612.3	711.09	705.4	725.84	808.7	740.13	923.0
2640	2180	685.84	546.0	701.79	632.8	717.22	729.8	732.15	837.5	746.61	956.7
2660	2200	691.61	563.6	707.75	653.9	723.36	754.9	738.47	867.1	753.11	991.4
2680	2220	697.38	581.6	713.72	675.6	729.51	780.6	744.80	897.6	759.61	1027.2
2700	2240	703.16	600.2	719.69	697.8	735.67	807.1	751.14	928.9	766.12	1064.0
2700	2240	703.16	600.2	719.69	697.8	735.67	807.1	751.14	928.9	766.12	1064.0
2720	2260	708.95	619.2	725.66	720.6	741.83	834.3	757.48	961.1	772.63	1101.9
2740	2280	714.74	638.6	731.65	744.0	748.00	862.2	763.83	994.2	779.16	1141.0

2760	2300	720.53	658.6	737.63	768.0	754.18	890.9	770.19	1028.3	785.69	1181.1
2780	2320	726.33	679.0	743.63	792.6	760.36	920.4	776.55	1063.3	792.23	1222.4
2800	2340	732.14	699.9	749.63	817.9	766.55	950.6	782.92	1099.2	798.77	1264.9
2820	2360	737.95	721.3	755.63	843.8	772.74	981.6	789.30	1136.1	805.33	1308.5
2840	2380	743.77	743.3	761.65	870.3	778.94	1013.5	795.68	1174.1	811.89	1353.4
2860	2400	749.59	765.8	767.66	897.5	785.15	1046.2	802.07	1213.1	818.46	1399.6
2880	2420	755.41	788.8	773.68	925.4	791.36	1079.7	808.47	1253.1	825.03	1447.1
2900	2440	761.24	812.3	779.71	954.0	797.58	1114.1	814.87	1294.2	831.61	1495.9
2920	2460	767.08	836.4	785.74	983.2	803.80	1149.3	821.28	1336.4	838.20	1546.0
2940	2480	772.91	861.1	791.78	1013.2	810.03	1185.5	827.69	1379.7	844.80	1597.5
2960	2500	778.76	886.4	797.82	1044.0	816.27	1222.6	834.12	1424.1	851.40	1650.4
2980	2520	784.61	912.2	803.87	1075.4	822.51	1260.6	840.54	1469.7	858.01	1704.7
3000	2540	790.46	938.6	809.93	1107.6	828.75	1299.6	846.98	1516.5	864.63	1760.5
3020	2560	796.32	965.7	815.98	1140.6	835.01	1339.5	853.42	1564.5	871.25	1817.9
3040	2580	802.18	993.3	822.05	1174.4	841.27	1380.5	859.87	1613.8	877.88	1876.7
3060	2600	808.05	1021.6	828.12	1209.0	847.53	1422.4	866.32	1664.3	884.51	1937.0
3080	2620	813.92	1050.5	834.19	1244.3	853.80	1465.4	872.78	1716.1	891.15	1999.0
3100	2640	819.79	1080.0	840.27	1280.6	860.07	1509.4	879.24	1769.2	897.80	2063
3120	2660	825.67	1110.2	846.35	1317.6	866.35	1554.4	885.71	1823.6	904.45	2128
3140	2680	831.55	1141.1	852.44	1355.5	872.63	1600.6	892.18	1879.4	911.11	2195
3160	2700	837.44	1172.6	858.53	1394.3	878.92	1647.8	898.66	1936.5	917.78	2263
3180	2720	843.33	1204.9	864.62	1433.9	885.22	1696.2	905.15	1995.1	924.45	2334
3200	2740	849.23	1237.8	870.73	1474.5	891.52	1745.8	911.64	2055	931.13	2406
3220	2760	855.13	1271.5	876.83	1515.9	897.82	1796.4	918.14	2117	937.81	2480
3240	2780	861.03	1305.8	882.94	1558.3	904.13	1848.3	924.64	2180	944.50	2556
3260	2800	866.94	1340.9	889.06	1601.7	910.45	1901.4	931.15	2244	951.20	2634
3280	2820	872.85	1376.8	895.17	1646.0	916.77	1955.7	937.66	2310	957.90	2714

(continued)

Table D.2 British Engineering (BE) units (continued)

T		$f = 0$		$f = 0.0169$		$f = 0.0338$		$f = 0.0507$		$f = 0.0676$	
°R	°F	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r	h, Btu/lbm	P_r
3300	2840	878.77	1413.4	901.30	1691.2	923.09	2011	944.18	2378	964.60	2795
3320	2860	884.69	1450.7	907.43	1737.5	929.42	2068	950.70	2447	971.31	2879
3340	2880	890.61	1488.8	913.56	1784.8	935.75	2126	957.23	2518	978.03	2965
3360	2900	896.54	1527.8	919.69	1833.1	942.09	2186	963.76	2590	984.75	3053
3380	2920	902.47	1567.5	925.83	1882.4	948.43	2246	970.30	2665	991.48	3143
3400	2940	908.40	1608.1	931.98	1932.8	954.78	2309	976.84	2741	998.21	3235
3420	2960	914.34	1649.4	938.12	1984.3	961.13	2372	983.39	2818	1004.95	3329
3440	2980	920.28	1691.6	944.27	2037	967.48	2437	989.94	2898	1011.69	3426
3460	3000	926.23	1734.7	950.43	2091	973.84	2503	996.49	2979	1018.43	3524
3480	3020	932.18	1778.6	956.59	2145	980.20	2571	1003.05	3062	1025.18	3626
3500	3040	938.13	1823.4	962.75	2201	986.57	2640	1009.62	3147	1031.94	3730
3500	3040	938.13	1823.4	962.75	2201	986.57	2640	1009.62	3147	1031.94	3730
3520	3060	944.08	1869.1	968.92	2258	992.94	2711	1016.19	3234	1038.70	3836
3540	3080	950.04	1915.7	975.08	2317	999.31	2783	1022.76	3323	1045.46	3944
3560	3100	956.00	1963.2	981.26	2376	1005.69	2857	1029.34	3414	1052.23	4055
3580	3120	961.96	2012	987.43	2437	1012.07	2933	1035.92	3507	1059.01	4169
3600	3140	967.93	2062	993.61	2499	1018.46	3010	1042.50	3602	1065.78	4285
3620	3160	973.90	2111	999.80	2562	1024.85	3088	1049.09	3699	1072.57	4404
3640	3180	979.87	2163	1005.98	2627	1031.24	3169	1055.68	3798	1079.35	4525
3660	3200	985.85	2215	1012.17	2692	1037.63	3251	1062.28	3899	1086.14	4649
3680	3220	991.83	2268	1018.36	2759	1044.03	3334	1068.88	4003	1092.93	4776
3700	3240	997.81	2322	1024.56	2828	1050.44	3420	1075.48	4109	1099.73	4906
3720	3260	1003.79	2378	1030.76	2897	1056.84	3507	1082.09	4217	1106.53	5039
3740	3280	1009.78	2434	1036.96	2969	1063.25	3596	1088.70	4327	1113.34	5174

3760	3300	1015.77	2492	1043.16	3041	1069.66	3686	1095.31	4439	1120.15	5313
3780	3320	1021.76	2550	1049.37	3115	1076.08	3779	1101.93	4554	1126.96	5455
3800	3340	1027.76	2610	1055.58	3190	1082.50	3873	1108.55	4672	1133.77	5599
3820	3360	1033.75	2670	1061.80	3267	1088.92	3970	1115.17	4792	1140.59	5747
3840	3380	1039.75	2732	1068.01	3345	1095.34	4068	1121.80	4914	1147.41	5898
3860	3400	1045.76	2795	1074.23	3425	1101.77	4168	1128.43	5039	1154.24	6052
3880	3420	1051.76	2859	1080.45	3506	1108.21	4270	1135.06	5166	1161.07	6210
3900	3440	1057.77	2924	1086.68	3589	1114.64	4374	1141.70	5296	1167.91	6371
3920	3460	1063.78	2990	1092.91	3673	1121.08	4481	1148.34	5429	1174.74	6535
3940	3480	1069.80	3058	1099.14	3759	1127.52	4589	1154.99	5564	1181.58	6703
3960	3500	1075.81	3126	1105.37	3847	1133.96	4699	1161.63	5702	1188.43	6874
3980	3520	1081.83	3196	1111.61	3936	1140.41	4812	1168.29	5843	1195.28	7049
4000	3540	1087.86	3268	1117.85	4027	1146.86	4927	1174.94	5987	1202.13	7227

Appendix E
Turbomachinery Stresses and Materials

E.1 Introduction

Even though the focus of this textbook is the aerothermodynamics of the gas turbine engine, the importance of the engine structure is also very significant. Because of its importance, this appendix addresses the major stresses of the rotating components and the properties of materials used in these components. The rotating components of the compressor and turbine have very high momentum, and failure of one part can be catastrophic, with a resulting destruction of the engine and, in the extreme, the aircraft. This is especially true of the "critical" parts of the turbomachinery such as the long first-stage fan blades and the heavy airfoils and disks of the cooled high-pressure turbine.

Over their lives, the rotating parts must endure in a very harsh environment where the loads are very dependent on the engine use. For example, an engine developed for a commercial aircraft will not be subjected to as many throttle excursions as one developed for a fighter aircraft. As a result, the "hot section" [combustor and turbine(s)] of the fighter engine will be subjected to many more thermal cycles per hour of operation than that of the commercial aircraft.

The main focus of the analytical tools developed in this appendix is on the fundamental source of stresses in rotating components—the centrifugal force. To get some idea of the brutal climate in which these components must live, the centrifugal force experienced by an element of material rotating at 10,000 rpm with a radius of 1 ft (0.3 m) is equivalent to more than 34,000 g. Yet, there are many other forces at work that can consume the life of (or destroy) rotating parts, all of which must be considered in the design process. Some of the most important include:

1) Stresses due to bending moments like those due to the lift on the airfoils or pressure differences across disks.

2) Buffeting or vibratory stresses that occur as the airfoils pass through nonuniform incident flows such as the wakes of upstream blades. This can be most devastating when the *blade passing* frequency coincides with one of the lower natural frequencies of the airfoils.

3) Airfoil or disk flutter, an aeroelastic phenomenon in which a natural frequency is spontaneously excited, the driving energy being extracted from the flowing gas. This is most often found in fan and compressor rows, and once it has begun, the life of the engine is measured in minutes.

4) Torsional stresses that result from the transfer of power from the turbine to the compressor.

5) Temperature gradients that can give rise to very high stresses. These can be very extreme during throttle transients when the engine is moving from one power setting to another. These cyclic thermal stresses extract life from components, especially in the hot section of fighter engines. This is commonly called *thermal* or *low-cycle* fatigue.

6) Local stress concentrations that result from holes, slots, corners, and cracks—the most feared of all.

7) Foreign object damage (FOD) and domestic object damage (DOD) that result from external and internal objects, respectively. The need to withstand FOD or DOD can dramatically impact the design. The use of lightweight, nonmetallic materials for large fan blades has been prevented for several decades due to requirement that they withstand bird strikes.

Each of these areas and many others are included in the design of engine components and material selection. After these are accounted for, an *allowable working stress* is developed and commonly used for the principal tensile stresses alone.

The next section analyzes dominant stresses in the rotating components. Figure E.1 depicts a turbine rotor with its airfoils, rim, and disk. A compressor or fan rotor is constructed similarly. However, the portion of the airfoil stresses carried by the compressor or fan's rim is much greater than that of a turbine rotor; hence, its disk is either much smaller or nonexistent. We consider the principal stresses of each part, starting with the airfoils.

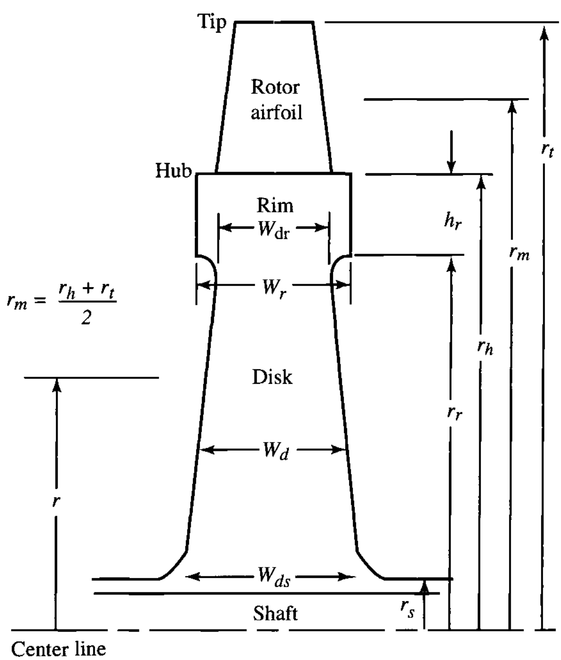

Fig. E.1 Turbomachinery rotor nomenclature.

E.2 Turbomachinery Stresses

E.2.1 Rotor Airfoil Centrifugal Stress σ_c

We start by considering the force in an airfoil at a cross section (see Fig. E.2). At any radius r, the force must restrain the centrifugal force on all the material beyond it. Thus the hub or base of the airfoil must experience the greatest force. The total centrifugal force acting on A_h is

$$F_c = \int_{r_h}^{r_t} \rho\omega^2 A_b r \, \mathrm{d}r \tag{E.1}$$

so that the principal tensile stress is

$$\sigma_c = \frac{F_c}{A_h} = \rho\omega^2 \int_{r_h}^{r_t} \frac{A_b}{A_h} r \, \mathrm{d}r \tag{E.2}$$

The airfoil cross-sectional area usually tapers down or reduces with, increasing radius, which, according to Eq. (E.2), has the effect of reducing σ_c. If the taper is *linear*, we can write

$$\frac{A_b}{A_h} = 1 - \left(1 - \frac{A_t}{A_h}\right)\left(\frac{r - r_h}{r_t - r_h}\right) \tag{E.3}$$

and Eq. (E.2) becomes

$$\sigma_c = \rho\omega^2 \left[\frac{A}{2\pi} - \left(1 - \frac{A_t}{A_h}\right) \int_{r_h}^{r_t} \left(\frac{r - r_h}{r_t - r_h}\right) r \, \mathrm{d}r\right] \tag{E.4}$$

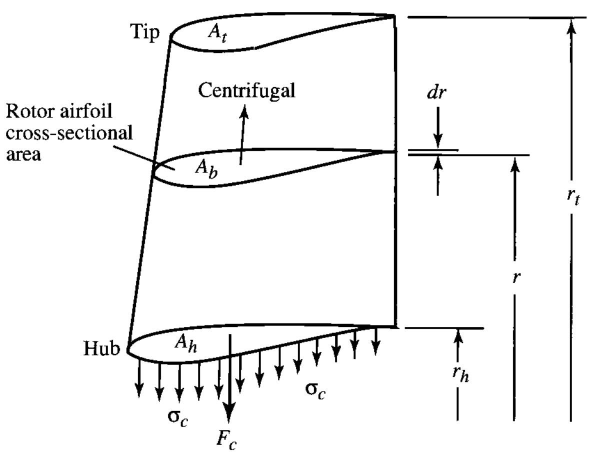

Fig. E.2 Rotor airflow centrifugal stress nomenclature.

where A is the flow path annulus area $\pi(r_t^2 - r_h^2)$. Integration of Eq. (E.4) gives

$$\sigma_c = \frac{\rho\omega^2 A}{4\pi}\left[2 - \frac{2}{3}\left(1 - \frac{A_t}{A_h}\right)\left(1 + \frac{1}{1 + r_h/r_t}\right)\right] \tag{E.5}$$

Equation (E.5) has an upper limit (corresponding to $r_h/r_t = 1$) of

$$\sigma_c = \frac{\rho\omega^2 A}{4\pi}\left(1 + \frac{A_t}{A_h}\right) \tag{E.6}$$

This equation reveals the basic characteristic that σ_c is proportional to $\rho\omega^2 A$. It also shows that tapering can, at most, reduce the stress of a *straight* airfoil (i.e., $A_t = A_h$) by half (i.e., $A_t = 0$).

Common practice in the industry is to refer to $\omega^2 A$ as the term AN^2 because it is easy to calculate and use. The COMPR computer program calculates and outputs AN^2 for each stage for proper material selection. For the TURBN computer program, the value of AN^2 is calculated and output for each stage.

We note that

$$AN^2 = A\omega^2\left(\frac{30}{\pi}\right)^2 \tag{E.7}$$

By using Eq. (E.7), we obtain for Eq. (E.6)

$$\frac{\sigma_c}{\rho} = AN^2 \frac{\pi}{3600}\left(1 + \frac{A_t}{A_h}\right) \tag{E.8}$$

For a fixed value of AN^2, Eq. (E.8) shows the obvious reduction in centrifugal stress by using more lightweight materials [e.g., titanium with a density of about 9 slug/ft^3 (about 4600 kg/m^3)] rather than the heavier materials [densities of about 16 slug/ft^3 (about 8200 kg/m^3)]. This equation is given in graphical form in Fig. E.3 for several different airfoil taper ratios A_t/A_h for AN^2 values from 0 to 6×10^{10} in.$^2\cdot$rpm^2 (3.87×10^7 m$^2\cdot$rpm^2).

Example E.1

In this example, we determine the centrifugal stresses at 10,000 rpm in typical airfoil materials of a compressor ($\rho = 9.0$ slug/ft^3) and turbine ($\rho = 15.0$ slug/ft^3) with flow annulus areas of 2.0 and 1.0 ft^2, respectively. Table E.1 summarizes the results, using Eq. (E.8) for an airfoil taper A_t/A_h of 0.8. For the compressor, $\sigma_c = (\pi/3.6)(9/1.44^2)(2.88)(1.8) = 19.63$ ksi. Even though the compressor centrifugal stress is higher than that in the turbine airfoil, the turbine airfoils are subjected to higher temperatures and will, most likely, have a lower *allowable working stress*.

E.2.2 Rim Web Thickness W_{dr}

The rotating airfoils are inserted into slots in an otherwise solid annulus of material known as the *rim* (see Fig. E.1), which maintains their circular motion. The airfoil hub tensile stress σ_c is treated as though "smeared out"

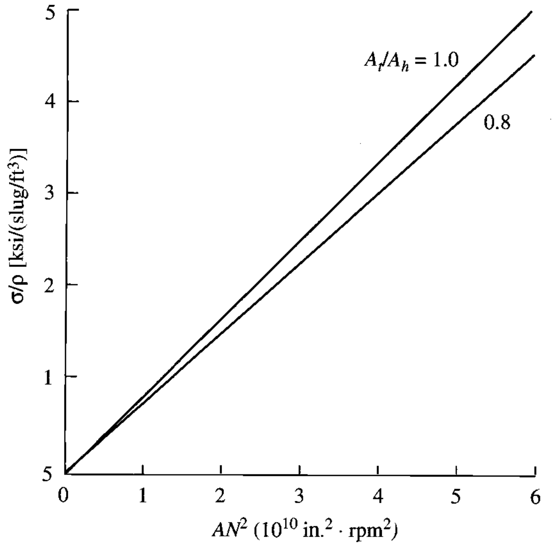

Fig. E.3 Variation of centrifugal stress-to-density ratio with AN^2.

over the outer rim surface, so that

$$\bar{\sigma}_{\text{blades}} = \frac{\sigma_c n_b A_h}{2\pi r_h W_r} \tag{E.9}$$

where n_b is the number of blades on the *wheel*.

Assuming uniform stress within the rim σ_r, we can use the force diagram of Fig. E.4 to determine the dimension W_{dr} (see Fig. E.1) necessary to balance

Table E.1 Centrifugal stress results for Example E.1

Variable	Compressor	Turbine
ρ slug/ft^3	9.0	15.0
(kg/m^3)	4611	7686
N rpm	10,000	10,000
A ft^2	2.0	1.0
(m^2)	0.186	0.0929
AN^2 in.^{2}·rpm^2	2.88×10^{10}	1.44×10^{10}
(m^2·rpm^2)	1.86×10^7	9.29×10^6
A_t/A_h	0.8	0.8
σ_c psi	19,630	16,360
(MPa)	135.3	112.8

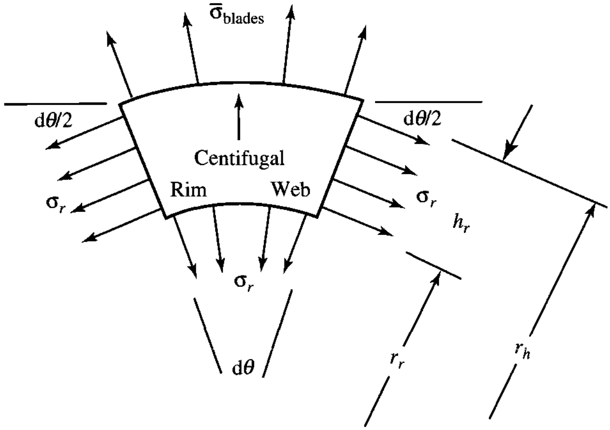

Fig. E.4 Rim segment radial equilibrium nomenclature.

the blade and rim centrifugal forces. Please note that W_r and h_r are simply sensible initial choices, where W_r approximates the axial chord of the airfoil and h_r is similar in magnitude to W_r. It is important to realize that it will always be possible to design a rim large enough to "carry" the airfoils. The real question is whether the size of the rim is practical from the standpoint of space required, weight, and manufacturing cost. Thus, there is no absolute solution, and the final choice must be based on experience and a sense of proportion.

A radial force balance of the differential rim element shown in Fig. E.4 gives

$$\bar{\sigma}_{\text{blades}} r_h W_r \, \mathrm{d}\theta + \rho\omega^2 h_r W_r (r_r + h_r/2)^2 \, \mathrm{d}\theta = \sigma_r r_r W_{\text{dr}} \, \mathrm{d}\theta + 2\left(\sigma_r h_r W_r \frac{\mathrm{d}\theta}{2}\right)$$

which, for any infinitesimal $\mathrm{d}\theta$, becomes

$$\frac{W_{\text{dr}}}{W_r} = \left[\frac{\bar{\sigma}_{\text{blades}}}{\sigma_r}\left(1 + \frac{r_r}{h_r}\right) + \frac{\rho(\omega r_r)^2}{\sigma_r}\left(1 + \frac{h_r}{2r_r}\right)^2 - 1\right]\frac{h_r}{r_r} \tag{E.10}$$

If σ_r is sufficiently large, this equation clearly shows that W_{dr} can be zero or less, which means that the rim is *self-supporting*. Nevertheless, a token disk may still be required to transfer torque to the shaft and, of course, to keep the rim and airfoils in the right axial and radial position.

Example E.2

Using typical values of the terms in Eq. (E.10) for the compressor and turbine based on disk materials given in Table E.2, Eq. (E.10) yields $W_{\text{dr}}/W_r = 0.37$ for the compressor and $W_{\text{dr}}/W_r = 0.56$ for the turbine.

Table E.2 Typical data for Example E.2

Variable	Compressor	Turbine
$\bar{\sigma}_{\text{blades}}/\sigma_r$	0.10	0.20
h_r/r_r	0.05	0.10
$\rho(\omega r_r)^2/\sigma_r$	6.0	4.0

E.2.3 Disk of Uniform Stress

The disk supports and positions the rim while connecting it to the shaft. Its thickness begins with a value of W_{dr} at the inside edge of the rim and must grow as the radius decreases because of the accumulating centrifugal force that must be resisted. Just as was found for the rim, a disk can always be found that will perform the required job, but the size, weight, and/or cost may be excessive. Thus the final choice usually involves trial and error and judgment.

It is impossible to overemphasize the importance of ensuring the structural integrity of the disks, particularly the large ones found in cooled high-pressure turbines. Because they are very difficult to inspect and because massive fragments that fly loose when they disintegrate cannot be contained, they must not be allowed to fail.

The most efficient way to use available disk materials is to design the disk for constant radial and circumferential stress. Because the rim and disk are one continuous piece of material, the design stress would be the same throughout ($\sigma_r = \sigma_d$).

Applying locally radial equilibrium to the infinitesimal element of the disk of Fig. E.5 leads to the equation

$$\rho(\omega r_r)^2 W_d \, \mathrm{d}r \, \mathrm{d}\theta = \sigma_d \left[\left(r - \frac{\mathrm{d}r}{2} \right) \left(W_d - \frac{\mathrm{d}W_d}{2} \right) \mathrm{d}\theta - \left(r + \frac{\mathrm{d}r}{2} \right) \left(W_d + \frac{\mathrm{d}W_d}{2} \right) \mathrm{d}\theta + 2 \left(W_d \, \mathrm{d}r \frac{\mathrm{d}\theta}{2} \right) \right]$$

which becomes in the limit

$$\frac{\mathrm{d}W_d}{W_d} + \frac{\rho\omega^2}{\sigma_d} \mathrm{d}\left(\frac{r^2}{2} \right) = 0$$

This equation may be integrated, by starting from $r = r_r$ and $W_d = W_{\text{dr}}$, to yield the desired result:

$$\frac{W_d}{W_{\text{dr}}} = \exp\left\{ \frac{\rho(\omega r_r)^2}{2\sigma_d} \left[1 - \left(\frac{r}{r_r} \right)^2 \right] \right\} \tag{E.11}$$

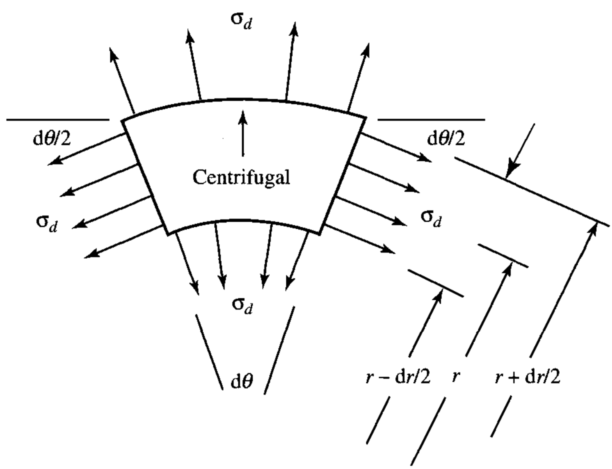

Fig. E.5 Disk element radial equilibrium nomenclature.

The fundamental feature of Eq. (E.11) is that the disk thickness W_d grows exponentially in proportion to $(\omega r_r)^2$, which is the square of the maximum or rim velocity of the disk. Because this parameter has such a great influence on disk design, it is normal to hear structural engineers talk in terms of *allowable wheel speed.*

Figure E.6 shows the thickness distribution for typical values of the *disk shape factor* (DSF) $\rho(\omega r_r)^2/(2\sigma_d)$ by using Eq. (E.11). Judging by the looks of these thickness distributions, the maximum allowable value of the disk shape factor

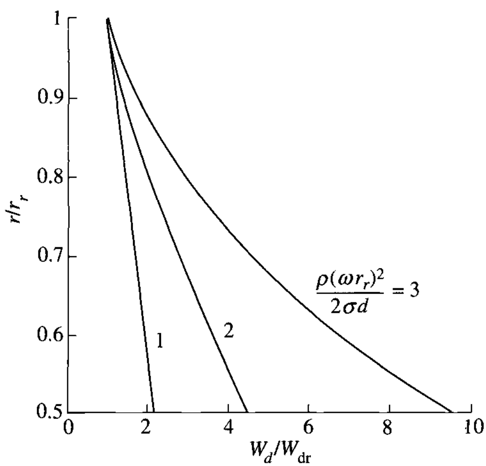

Fig. E.6 Disk thickness distributions.

is not much more than 2, so that

$$\omega r_r \approx \sqrt{\frac{4\sigma_d}{\rho}} \tag{E.12}$$

Note: At this point it should be apparent that, on the low-pressure spool where the annulus flow area A is largest, the rotational speed (ω or N) is most likely to be limited by the allowable blade centrifugal stress [Eq. (E.6) or Eq. (E.8)]. Conversely, on the high-pressure spool, where the annulus flow area is considerably less, the rotational speed will probably be limited by the allowable wheel speed [Eq. (E.12)].

Example E.3

Determine the allowable wheel speed for the typical compressor and turbine materials. The compressor material has $\sigma_d = 30$ ksi, $\rho = 9.0\ \mathrm{slug/ft^3}$, and thus $\sigma_d/\rho = 4.8 \times 10^5\,\mathrm{ft^2/s^2}$ ($4.46 \times 10^4\,\mathrm{m^2/s^2}$). The turbine material has $\sigma_d = 20$ ksi, $\rho = 16.0\ \mathrm{slug/ft^3}$, and thus $\sigma_d/\rho = 1.8 \times 10^5\ \mathrm{ft^2/s^2}$ ($1.67 \times 10^4\ \mathrm{m^2/s^2}$). Using Eq. (E.12), we see that the allowable wheel speed for the compressor is about 1400 ft/s (420 m/s) and that for the turbine is about 850 ft/s (260 m/s). This indicates that the allowable wheel speed is more likely to limit the design of a turbine than the design of a compressor.

E.2.4 Disk Torsional Stress τ_d

The tangential disk shear stress required to transfer the shaft horsepower to the airfoils is easily calculated, since

$$\mathrm{HP} = \text{shear stress} \times \text{area} \times \text{velocity}$$

Thus

$$\tau_d = \frac{\mathrm{HP}}{2\pi r^2 W_d \omega} \tag{E.13}$$

Example E.4

Determine the disk torsional stress for the following typical values:

$$\mathrm{HP} = 10{,}000\,\mathrm{hp}\ (7457\,\mathrm{kW})$$
$$r = 0.30\ \mathrm{ft}\ (0.0914\,\mathrm{m})$$
$$W_d = 0.10\ \mathrm{ft}\ (0.0305\,\mathrm{m})$$
$$\omega = 1000\,\mathrm{rad/s}$$

Equation (E.13) gives $\tau_d = 675$ psi (4.65 MPa), which makes a relatively small contribution to the overall stress.

E.2.5 Disk Thermal Stress σ_{tr} and $\sigma_{t\theta}$

For a disk of constant thickness with no center hole and a temperature distribution that depends only on radius [$T = T(r)$], it can be shown (Ref. 44) that the radial tensile stress is

$$\sigma_{tr} = \alpha E\left[\frac{1}{r_h^2}\int_0^{r_h} T(r)\mathrm{d}r - \frac{1}{r^2}\int_0^{r} T(t)\,\mathrm{d}r\right] \tag{E.14}$$

where α is the coefficient of linear thermal expansion and E is the modulus of elasticity, and the tangential tensile stress is

$$\sigma_{t\theta} = \alpha E\left[\frac{1}{r_h^2}\int_0^{r_h} T(r)\,\mathrm{d}r + \frac{1}{r^2}\int_0^{r} T(r)\,\mathrm{d}r - T\right] \tag{E.15}$$

both of which are zero if the temperature is constant. An interesting illustrative case is that of the linear temperature distribution $T = T_0 + \Delta T\ (r/r_h)$, for which Eq. (E.14) becomes

$$\sigma_{tr} = \frac{\alpha E\,\Delta T}{3}\left(1 - \frac{r}{r_h}\right) \tag{E.16}$$

and Eq. (E.15) becomes

$$\sigma_{t\theta} = \frac{\alpha E\,\Delta T}{3}\left(1 - 2\frac{r}{r_h}\right) \tag{E.17}$$

both of which have a maximum magnitude of $\alpha E\ \Delta T/3$ at $r = 0$.

Example E.5

For typical values of $\alpha = 1 \times 10^{-5}$(°F) [$1.8 \times 10^{-5}$ 1(°C)$^{-1}$], $E = 10 \times 10^6$ psi (6.9×10^4 MPa), and $\Delta T = 100$°F (55.6°C), the maximum magnitude of σ_{tr} and $\sigma_{t\theta}$ is 6700 psi (46 MPa)! This simple case demonstrates forcefully that thermal stresses can be very large and, therefore, must be carefully accounted for and reduced as much as possible. This is especially true during transient operation.

With this perspective, it is possible to imagine that truly enormous stresses could be generated in the thin outer wall of the cooled turbine airfoils, if they are not very carefully designed. Because such stresses will be proportional to the temperature difference between the mainstream and the cooling air, there is also a limit to how cold a coolant may be used before it no longer truly *protects* the material.

Table E.3 Material types

Material no.	Type	Density slug/ft^3	Density kg/m^3
1	Aluminum alloy	5.3	2716
2	Titanium alloy	9.1	4663
3	Wrought nickel alloy	16.0	8200
4	High-strength nickel alloy	17.0	8710
5	Single-crystal superalloy	17.0	8710

E.3 Engine Materials

The harsh environment of the gas turbine engine requires special materials. Many of these materials are developed exclusively for this application by material experts—most of these experts work for either an engine company or a materials company. Therefore, the properties of many materials used for critical components in gas turbine engines are corporate secrets, and published data are limited. However, some materials have been and continue to be developed in the public sector, and their properties can be found in references such as the *Aerospace Structural Metals Handbook* (Ref. 87) and *The Superalloys* (Ref. 88), textbooks (Refs. 89 and 90), and journals (Ref. 91).

To provide examples and general guidance, the data for several materials commonly found in critical parts of gas turbine engines are given in Table E.3 and

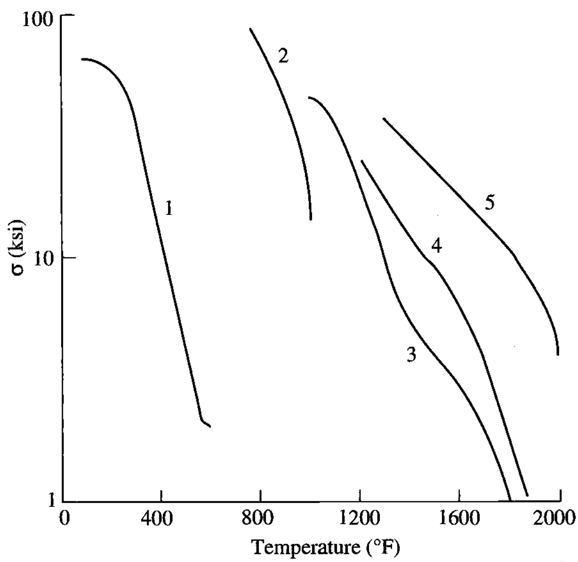

Fig. E.7 Strength at 1% creep for 1000 h.

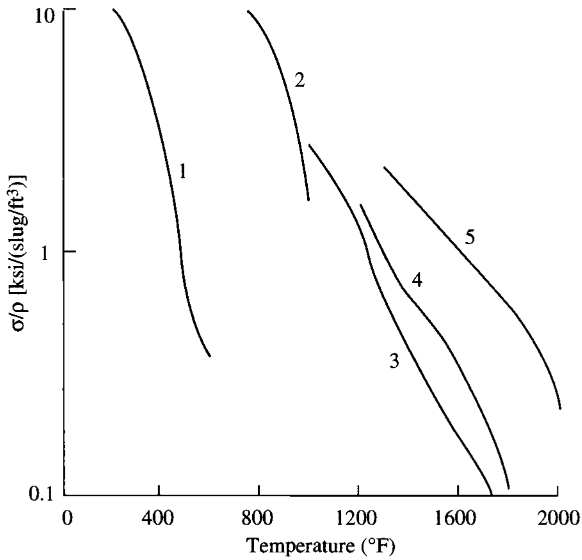

Fig. E.8 Strength-to-weight ratio at 1% creep for 1000 h.

Figs. E.7 and E.8. Figure E.7 gives the 1% creep curves of typical materials for 1000 h at temperatures between 0 and 2000°F. Dividing the material's creep strength by its density gives the material's strength/weight ratio. The variations of strength/weight ratio with temperature are given in Fig. E.8.

E.3.1 Compressor and Fan Materials

Normal practice for compressor and fan blades is to base designs on creep and creep-rupture data. Common practice is to allow less than 1% creep during the life of the part. A reasonable estimate of the *allowable working stress* is 30–50% of the value obtained from Fig. E.7 for 1000 h. For example, Fig. E.7 gives a 1% creep stress for material 1 of about 32 ksi at 300°F (220 MPa at 150°C) and 1000 h. Thus the *allowable working stress* for this material at these conditions would be from 10 to 16 ksi (70–110 MPa).

During its life, a fan or compressor blade is subjected to billions of *high-cycle fatigue* cycles due to vibrations. Thus it is important that the *run-out* stress, which the material can apparently withstand forever, not be exceeded. Aluminum 2124 alloy has a low run-out stress of about 12 ksi at room temperature while titanium 6246 alloy has a high run-out stress of about 140 ksi (about 1 MPa) at room temperature.[87] Because of the poor fatigue characteristics of aluminum alloys, titanium alloys are typically used for fan and low-pressure compressor blades and disks.

Titanium's strength/weight ratio is severely reduced at temperatures above 900°F (480°C). Hence nickel-base alloys are commonly used for the critical components of high-pressure compressors.

E.3.2 Turbine Materials

The critical components of the turbine are exposed to very high temperatures. Many of these parts require super materials, commonly called *superalloys*, and compressor air for cooling. Certain materials and environments also require protective coatings. Typical examples of these materials are Mar-M 509, a high-chromium, carbide-strengthened, cobalt-base superalloy, and René 80, a cast, precipitation-hardenable, nickel-base superalloy.[87] Many of the newer superalloys for turbine rotor blades are cast and solidified in such a manner as to align the crystals in the radial direction, called *directional solidification*, or to produce a single crystal. The resulting turbine blades are capable of operating at temperatures 100–200°F (55–110°C) above those of conventionally cast blades.

In high-pressure turbines, the blades are typically made of superalloys while high-strength, nickel-base alloys are used for the disks and rims. Because the temperatures are much lower in the low-pressure turbine, the critical components are not cooled and are frequently made from high-strength, nickel-base alloys.

Appendix F
About the Software

A comprehensive set of software is included to assist you in learning the text material, solving some of the problems in the text, and completing your design problems. The software programs use pull-down menus and edit fields that support a mouse to make them very user-friendly.

The AFPROP program defines the properties of air with hydrocarbon fuels and is provided in both executable and BASIC source code. The ATMOS program gives the properties of the atmosphere at any altitude for the user-selected temperature profile (standard, cold day, hot day, or tropic). The EQL program performs chemical equilibrium analysis for reactive mixtures of perfect gases. The GASTAB program gives complete one-dimensional gas dynamics tables for the user-selected ratio of specific heats.

PARA and PERF are a set of user-friendly computer programs written for the preliminary analyses of common airbreathing aircraft engine cycles. COMPR and TURBN are a set of computer programs that perform the preliminary analyses of axial-flow compressors and turbines, respectively. These programs allow you to solve a single problem, a number of "what if" solutions, or a design problem.

The current version of PARA, PERF, COMPR, and TURBN are written in Microsoft Visual Basic 6 with plotting procedures from APEX's Olectra Chart. Comprehensive user guides provided with the software will help answer most of your questions about the software.

F.1 Getting Started

To get started, you need a PC-compatible system with Microsoft Windows operation system (98 or later). The software is downloaded from the AIAA web site at *www.aiaa.org/publications/supportmaterials*. Follow the instructions provided and enter the following password: **GTandR2**.

Save the downloaded file and unpack into the files necessary for installation. Run the **Setup** program within the **EOP Software** folder and the opening installation window is displayed as shown in Fig. F.1

Select the OK button and the software destination window is displayed as shown in Fig. F.2.

Select the highlighted button in the upper left to install the programs in the default location (C:\Programs\EOP). The program group window is displayed as shown in Fig. F.3. It is recommended that the user uses the **EOP Software**

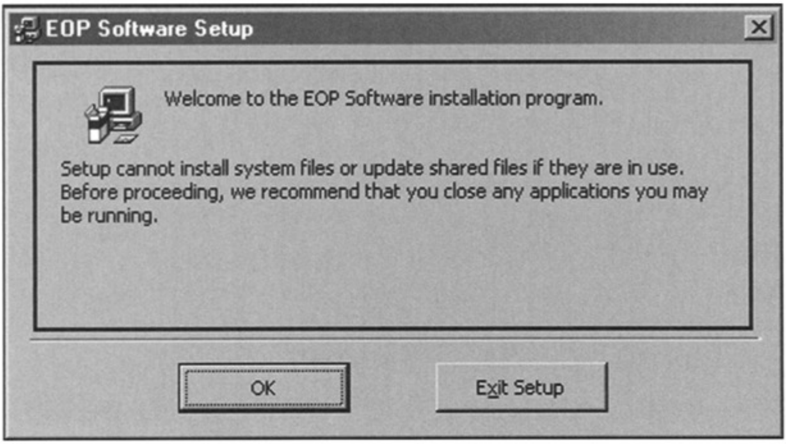

Fig. F.1 Opening installation window.

program group and presses the **Continue** button. Software installation will then proceed.

F.2 The Software

F.2.1 AFPROP.EXE (and AFPROP.BAS)

This program calculates the thermodynamic properties of air and fuel as a function of temperature and fuel/air ratio by using the equations in Chapter 2. Written in Microsoft Visual Basic 6, this program is supplied in both executable form (AFPROP.EXE) and source code (AFPROP.BAS). The source code can be used to write your own analysis programs with variable specific heats as discussed in Supporting Materials for Chapters 7 and 8.

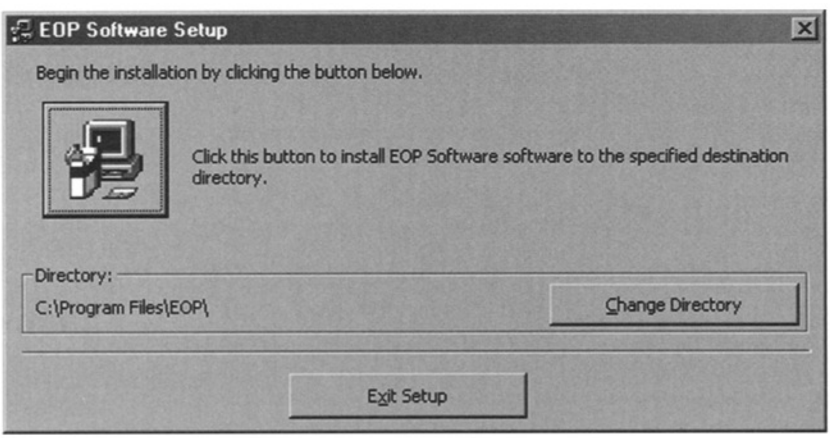

Fig. F.2 Installation destination window.

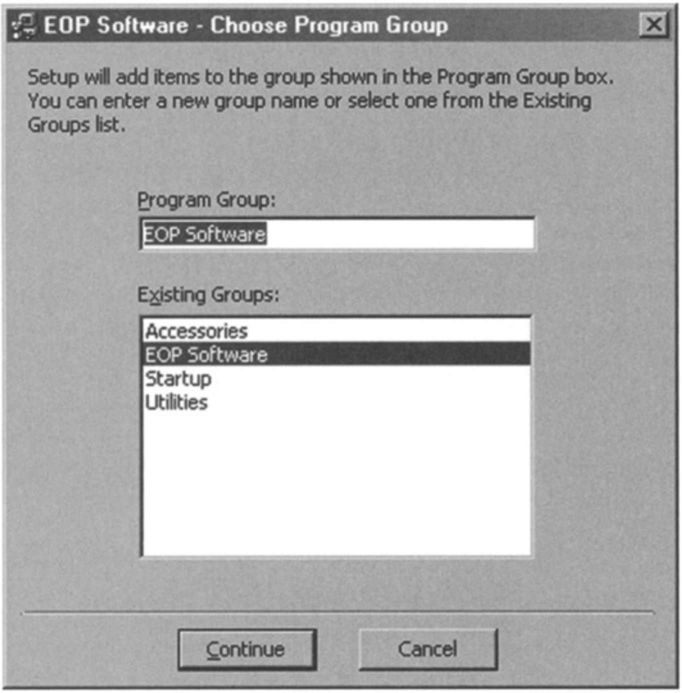

Fig. F.3 Program group window.

After selecting the unit system (English or SI), the user enters the fuel/air ratio and the temperature, or the enthalpy, or the reduced pressure. Input temperatures are limited to the range of 300°R (167 K) to 4000°R (2222 K), and the fuel/air ratio has a maximum value of 0.0676. The program will calculate the other properties in addition to the gas constant, specific heat at constant pressure, ratio of specified heats, and speed of sound.

F.2.2 ATMOS Program

This program calculates properties of the atmosphere for standard, cold, hot, and tropical days in either SI or English units.

F.2.3 EQL Program

The EQL program calculates equilibrium properties and process end states for reactive mixtures of perfect gases, for different problems involving hydrocarbon fuels. It supports the thermochemical analysis and problem in Chapters 2 and 3.

F.2.4 GASTAB.EXE

This program is equivalent to extensive, traditional, compressible flow appendices for the simple flows of calorically (constant specific heats) perfect gases.

It includes isentropic flow; adiabatic, constant area frictional flow (Fanno flow); frictionless, constant area heating and cooling (Rayleigh flow); normal shock waves; oblique shock waves; multiple oblique shock waves; and Prandtl-Meyer flow. The user inputs the ratio of specific heats γ, the mean molecular weight $\mathscr{M}$, and the known property. Then one clicks the check box beside this property and all other properties are calculated and displayed for that flow. The user can select the unit system (SI or English).

F.2.5 PARA.EXE

The PARA computer program determines the variation in gas turbine engine performance with cycle design variables such as the compressor pressure ratio. The program is based on the engine models contained in Chapters 5–7 of this book and is intended to be used with this textbook. The user can select the unit system (SI or English), the type of analysis model (ideal or real), the engine cycle (one of the eight engine cycles listed next), and the iteration variable (one of the five variables listed next or single-point calculation) along with its applicable range and increment. Data are entered and/or changed on data screens through edit fields. Results can be plotted on the screen by using defined ranges of plot data. In addition, the temperature vs entropy of the defined ideal engine cycle data can be plotted on the screen. The engine cycles and iteration variables are the following:

Engine cycles	**Variables**
Turbojet—single spool	Single point calculation
Turbojet—dual spool	Mach number
Turbojet with afterburner	Combustor exit temperature
Turbofan with two exhausts	Compressor pressure ratio
Turbofan with mixed exhaust	Fan pressure ratio
Turbofan with afterburning	Bypass ratio
Turboprop	
Ramjet	

This program is very useful for examining the trends of a selected engine cycle's specific performance (specific thrust and thrust specific fuel consumption) with changes in applicable design variables. Up to 21 sets of results can be plotted at a time. When one variable is used for calculations, results can be plotted vs the iteration variable. If more than one variable is used for calculations, only the specific performance (thrust specific fuel consumption vs specific thrust) of the cycle can be plotted.

The PARA program must have the default data file (PARA.PCA) in the same directory as the program. If the file is not in the current directory, the program will prompt you for the name of a Parametric Cycle Analysis file (*.PCA) as input.

F.2.6 PERF.EXE

The PERF computer program determines the performance of a specific engine and its variation with flight condition and throttle. The program is based on the engine models contained in Chapter 8 of this book and is intended to be used with this textbook. Through pull-down menus, the user can select the specific engine cycle (one of the eight engine cycles listed next) and its design, the iteration variable (one of the eight variables listed next) along with its applicable range and increment, the control system limits (e.g., temperature leaving compressor), the unit system (SI or English), and the output device(s). Data are entered and/or changed on a data screen through edit fields. Results can be plotted on the screen by using defined ranges of plot data. The engine cycles and iteration variables are the following:

Engine cycles	**Variables**
Turbojet—single spool	Single point @% thrust
Turbojet—dual spool	Mach number
Turbojet with afterburner	Altitude
Turbofan with separate exhausts	Ambient temperature
Turbofan with mixed exhaust	Ambient pressure
Turbofan with afterburning	T_{14}—total temperature leaving combustor
Turboprop	T_{17}—total temperature leaving afterburner
Ramjet	Exit nozzle pressure ratio (P_0/P_9)

PERF is very useful for examining the variation of an engine's performance with changes in flight condition, throttle, and control system limits. Up to 21 sets of results can be plotted at a time. When one variable is used for calculations, results can be plotted vs the iteration variable. If more than one variable is used for calculations, only the thrust specific fuel consumption vs thrust of the engine can be plotted.

The PERF program must have the default data file (PERF.EPA) in the same directory as the program. If the file is not in the current directory, the program will prompt you for the name of an Engine Performance Analysis file (*.EPA) as input.

F.2.7 COMPR.EXE

The COMPR program calculates the change in properties along the mean line of a multistage, axial-flow compressor based on user input data. The program is based on the methods contained in Chapter 9 of this book and is intended to be used with this textbook. The user can select the type of design (one of the five types of design listed next), type of swirl distribution (one of the three swirl distributions listed next), and unit system (SI or English). Data are entered and/or changed on a data screen through edit fields. The results are given for the hub, mean, and tip radius for both rotor and stator blades of each stage and include flow angles, diffusion factors, degree of reactions, pressures, Mach numbers, temperatures, velocities, number of blades, and blade centrifugal stress. The types of design and swirl distributions are the following:

Type of design	**Swirl distribution**
Constant tip radius	Free vortex
Constant mean radius	Exponential
Constant hub radius	First power
User-specified tip radius	
Repeating row/stage	

After stage calculations are completed, the user can have the computer sketch a cross-sectional drawing on the graphics screen (e.g., see Figs. 9.33, 9.36a, and 9.36b). The user can also have the computer sketch the relative position and angle of rotor and stator blades, using the NACA 65A010 profile for a specified stage and number of blades. One can also look at the change in spacing and blade angles with changes in radius (e.g., see Figs. 9.30 and 9.31).

The COMPR program must have the default data file (COMPR.CMP) in the same directory as the program. If the file is not in the current directory, the program will prompt you for the name of a COMPR file (*.CMP) as input.

F.2.8 TURBN.EXE

The TURBN program calculates the change in properties along the mean line of a multistage, axial-flow turbine based on user input data. The program is based on the methods contained in Chapter 9 of this book and is intended to be used with this textbook. The user can select the unknown (one of the five cases listed next), the loss model (one of the two listed next), and the unit system (SI or English). Data are entered and/or changed on a data screen through edit fields. The results are given for the hub, mean, and tip radius for both stator and rotor blades of each stage and include flow angles, degree of reactions, pressures, Mach numbers, temperatures, velocities, number of blades, and solidities. The unknowns and loss models are the following:

Unknown	**Loss model**
Flow angle entering rotor	Polytropic efficiency
Flow angle leaving rotor—Case I	Loss coefficient
Flow angle leaving rotor—Case II	
Mach number entering rotor	
Total temperature leaving rotor	

After stage calculations are completed, the user can have the computer sketch a cross-sectional drawing of the turbine on the graphics screen (e.g., see Figs. 9.72, 9.76, and 9.78). The user can also have the computer sketch the relative position and angle of rotor and stator blades, using the British C4 or T6 profile for a specified stage and number of blades. One can also look at the change in spacing and blade angles with changes in radius (e.g., see Figs. 9.77, 9.79, and 9.80).

The TURBN program must have the default data file (TURBN.TBN) in the same directory as the program. If the file is not in the current directory, the program will prompt you for the name of a TURBN file (*.TBN) as input.

Appendix G
Answers to Selected Problems

1.1	50 kN
1.4	1973 ft/s
1.8	194,080 N, 33%, 10.23 (mg/s)/N
1.10	193.4 ft/s
1.11	78.5 m/s
1.14	(a) 7.906, 0.3162, 0.04; (b) 39.8 kft, 5,690 lbf; (c) 45 kft, 4,430 lbf; (d) 1,140 nm
1.15	(a) 5.774, 0.3464, 0.06; (b) 6.65 km, 19,050 N; (c) 12.07 km, 19,050 N
1.16	(a) 1,257 nm; (b) 1,127 nm
1.19	(a) 10.2, 0.2449, 0.024, 0.7946; (c) 0.80; (d) 0.76
1.20	9,970 s
1.22	5 kN, 91.84 s
1.23	(a) 14,700 m/s; (b) 568 kg/s
2.1	2,970 lbf
2.6	28,950 lbf
2.8	53,800 N
2.9	135,900 lbf
2.12	772.9 K, 0.22 m^2, 0.19 m^2
2.14	18.34 MW (24,590 hp)
2.16	(a) 98.6 lbm/s; (b) 904°R, 66.5 psia; (c) 1.69 ft^2
2.19	(a) 81.3 kg/s; (b) 1009.4 K, 1.601; (c) 0.307 m^2, −48,660 N
2.21	20.43 MW, 0.0988 m^3/kg, 17.61 J/(kg-K)
2.22	2880.7°R, 29.30 MW, 0.0077 Btu/(lbm-°R)
2.30	315.7°R, 1.7085, 1488 ft/s, 0.3929 ft^2
2.32	86.01 MW (115,340 hp)
2.34	6.87 kg/s, 0.263, 295.9 K, 90.53 m/s
2.39	311.1°R, 12.78 psia, 1729 ft/s; 560°R, 72.09 psia, 5525°R, 7.51 psia, 648.5 ft/s
2.41	(a) 0.2117 m^2; (b) 0.03811 MPa, 125 K; (c) 0.4752, 0.4597 MPa, 0.3938 MPa, 350 K, 334.9 K; (d) 0.1797, 0.4495 MPa, 347.8 K
2.44	27.38 deg, 96.3 psia, 500°R, 5.59 psia, 221.7°R
3.2	5,660 lbm/s
3.4	10.465

3.5	126,900 kg
3.8	6185 ft/s
3.11	227,980 N
3.13	1.820
3.16	(a) 250 lbm/s; (c) 758.9 psia; (e) 1.830; (g) 54 kft; (h) 78,830 lbf
3.21	(a) 2.529; (d) 4.323 lbm/s; (f) 1.405; (h) 180.4 s
4.1	108.9 kM, 1.64 kN
4.3	4,400 lbf
4.5	7.7 kN
4.6	0.045, 0.060
4.9	267.6 N
5.7	3.916, 7123 N/(kg/s), 35.8 (mg/s)/N
5.18	2.686
5.19	0.9425
6.4	(a) 0.8623, 0.8849, 0.8923, 0.9074; (b) 0.8932, 0.8739; (c) 0.9461, 1.8125, 0.8861, 2.037
6.5	0.979
6.6	0.670
6.7	(a) 0.9561, 0.9585; (b) 0.8594, 0.8737, 0.8996, 0.925; (c) 0.9225, 0.8924; (d) 30,035 hp (22.4 MW), 12,776 hp (9.53 MW), 57,702 hp (43.03 MW); (e) 105,160 hp (78.42 MW)
7.8	390 kPa, 540.6 K, 188.5 kPa, 1550.1 K, 1.724
7.9	(a) 5.502 ft^2; (b) 3.548 ft^2; (c) 8.165 lbm/s, 5.405 ft^2
7.11	Compressor pressure ratio range from 17.8 to 53
7.15	15.45 lbf/(lbm/s), 0.6075 (lbm/h)/lbf
SM7.1	111.9 lbf/(lbm/s), 1.852 (lbm/h)/lbf
SM7.3	Compressor pressure ratio range from 14.84 to 19.9 with a corresponding fan pressure ratio range of 2.860 to 2.847
SM7.8	$M_9 = 0.7657$, 1242 N/(kg/s), 16.05 (mg/s)/N
SM7.9	Compressor pressure ratio range from 10.83 to 17.71 with a corresponding turbine temperature ratio range of 0.5996 to 0.5400
8.2	(a) 0.0004508, 132.58; (b) 4.055, 16.28 kg/s; (c) 1620 K, 8, 25 kg/s, 1800 K, 6.92, 22.67 kg/s
8.6	(c) $M_9 = 2.715$, 605 N/(kg/s), 57.74 (mg/s)/N
8.7	2.2657, 14.316, 0.7750
8.8	$M_9 = 1.6276$, 18.622 kg/s, 10,590 N
8.9	(a) 97.0 lbm/s, 3.5124, 5.5672, 3223.6 ft/s, 10,129 lbf, 1.4445 (lbm/h)/lbf; (b) 4.7109, 86.01 lbm/s, 2.7578, 4.6393, 0.9129; (c) 5.3276, 92.74 lbm/s, 3.1188, 5.1032, 0.9574
8.14	525.8 lbm, 7,111 lbf, 0.6263 (lbm/h)/lbf
8.15	1918 lbm/s, 68,330 lbf, 0.3772 (lbm/h)/lbf

9.2	20.86 m/s, 41.72 m/s
9.3	120 m/s, 1.328
9.6	(a) 646.9 ft/s, 495.6 ft/s, 415.8 ft/s; (b) 495.6 ft/s, 783.0 ft/s, 926.7 ft/s; (c) 73.36°R, 1.1414; (d) 1.5168, 22.29 psia
9.11	Betal = 56.468, Stage pressure ratio = 1.3444
9.18	3.129×10^{10} in.^{2}-rpm^2
9.19	2133.5 rad/s, 163.2 K, 82.0%, 327.7 kW
9.21	(a) 827.82 m/s, 585.36 m/s, 585.36 m/s; (b) 585.36 m/s, 51.21 m/s, 587.6 m/s; (c) −184.26 K, 0.89763; (d) 0.59106, 591.06 kPa
9.28	5.282×10^6m^2-rpm^2
9.30	(a) 0.1569 m^2; (b) 5561 rpm; (c) 0.64027 m, 0.62014 m, 200.9 K
9.33	(a) 1440.5 ft/s, 2160.7 rad/s; (b) 0.850; (c) 96.3 psia; (d) 0.8614
9.34	(a) 155.46 m/s, 309.86 K; (b) 145.32 m/s, 1.128 atm; (c) 881.75 K; (d) 0.0742 m, 0.0694 m

10.2	1.636 ft
10.3	2.039 m
10.4	0.282 m
10.5	(a) 1.9228; (b) 1.697; (c) 0.7544; (d) 1.534
10.6	(a) 1.27924, 0.71204; (b) 0.52442
10.9	1.39, 0.6572
10.11	(a) 0.9122, 0.7209; (b) Fraction spilled = 12.7%
10.17	$C_V = 0.9937$, $C_{fg} = 0.9764$, $F_{g\ \text{actual}} = 92{,}583$ N
10.19	0.4103 m
10.21	0.9930, 0.0909
10.23	0.99884, 0.0249
10.25	10
10.27	98.5%
10.28	0.782 to 1.564 ft^3