

dards are different for various types of vehicles. Present-day standards in the Federal Government and California State require that there should be no emission from the crankcase of a light duty gasoline vehicle, while the evaporative loss of hydrocarbons should be less than 6 g/test. Table 18.4 shows the exhaust emission standards that were required to be met in previous years. The requirements were continuously made more stringent as research indicated the technical feasibility of such goals to be achieved. Table 18.4 indicates the emission by an uncontrolled vehicle.

TABLE 18.4 Exhaust Emission Standards for Light Duty Vehicles (with permission of John Wiley and Sons from James N. Pitts Jr. and K.L. Metcalf (Ed.): *Advances in Environmental Science and Technology*, 1971, II: 77)

Uncontrolled emissions, g/mile	Exhaust emission standards		Remarks
	Model	Year	
1970	HC	2.2	Federal and California
	CO	23	Federal and California
	HC	2.2	Federal and California
1971	CO	23	Federal and California
	NO _x	4.0	California
	HC	1.5	California
1972	CO	23	Federal and California
	NO _x	3.0	California
	HC	1.5	California
1974	CO	23	Federal and California
	NO _x	1.3	California
	HC	0.5	California
1975	CO	12	California
	NO _x	1.0	California
	HC	1.1	California
CO**	80		
NO _x [†]	5.7		

*HC—Hydrocarbons, as measured by nondispersive infrared analyzer (NDIR)

**CO—Carbon monoxide

[†]NO_x—Oxides of nitrogen, expressed as nitrogen dioxide

The requirements for a heavy duty diesel vehicle are not too difficult to achieve. Federal government requirements limit the smoke from 1970 model diesel engines to an opacity that should not exceed 40% during acceleration and 20% during the engine lagging mode. The hydrocarbon and carbon monoxide concentrations emitted by a diesel vehicle are usually within the standards prescribed for heavy duty vehicles. The 1972 standard requirements in California State for a heavy duty vehicle, limits the hydrocarbon emission to 180 ppm while the carbon monoxide limit is 1.0%. The concentration of carbon monoxide in a diesel engine exhaust is usually 0.1 to 0.3%.

APPENDICES

APPENDIX A

TABLE A.1 Coal, Reserves and Production

Country	Date	Reserves (Million tonnes)		Total	Production (Thousand tonnes)	
		Measured	Inferred		Average 1964-68	1972
World Total	...	...	...	6641200	1988300	2144800
Afghanistan	1965	...	...	85	139	...
Algeria	1957	9	11	20	31	...
Argentina	1966	374	76	450	390	675
Australia	1966-67	3000	13000	16000	30252	49056
Austria	1966	...	3	3	39	...
Belgium	1964-67	495	1301	1796	17966	10500
Botswana	1961	506	...	...	...	...
Brazil	1966	3175	7500	10675	2154	2497
Bulgaria	1965	1147	...	1147	512	384
Burma	1960	13	8	21	13	16
Canada	1966	42600	18400	61000	8267	15810
Chile	1966	96	122	218	1490	1332
China	1913	...	...	1011000	288000	400000
Colombia	...	...	...	12500	2954	2800
Czechoslovakia	1966	5540	6033	11573	26886	27925
France	1966	...	...	2800	48850	29763
German Dem. Rep.	1956	...	...	50	1981	815
Germany, Fed. Rep. of	1967	70000	...	...	125784	102707
Greenland	1967	2	...	...	27	4
Hungary	1966	...	...	714	4228	3671
India	1966	12710	93550	106260	67322	74771
Indonesia	1962	500	345	845	308	179
Iran	1961	...	...	1000	286	1000
Ireland	1967	22	26	48	196	82
Italy	...	...	...	...	410	151
Japan	1961	5723	13525	19248	49172	28098
Korea, Dem. People's Rep. of	...	...	...	...	15720	...
Korea, Rep. of	1962	85	1100	1185	10832	12403
Madagascar	1963	60	...	...	2	...
Mexico	1966	182	3284	3466	1293	2170
Mongolia	...	...	...	...	54	106
Morocco	1960	15	81	96	441	547
Mozambique	1963	...	...	700	275	336
Netherlands	1956	2394	...	2394	9541	2812
New Zealand	1967	297	533	830	637	418

(Contd)

TABLE A.1 (Cont'd)

Country	Reserves (Million tonnes)			Production (Thousand tonnes)	
	Date	Measured	Inferred	Average 1964-68	1972
Nigeria	1961	...	350	664	341
Norway	1967	16	150	415	455
Pakistan	1966	784	877	1661	1235
Peru	1966	211	2123	2334	1251
Philippines	...	...	...	151	...
Poland	1967	32425	13316	45741	39
Portugal	1960	15	11	122136	150697
Romania	1966	...	...	26	252
South Africa	1959	36873	35592	590	4913
South Rho- desia	1960	1760	4853	72465	48455
Spain	1960	2830	...	6613	2881
Swaziland	1961	2022	3000	...	12540
Sweden	1967	60	30	5022	63
Turkey	1957	205	1130	90	43
USSR	1966	145123	3976480	1335	4615
Ukrainian SSR	...	...	...	4121603	403212
United Kingdom	1967	12227	3273	...	163501
United Rep. of Tanzania	1967	309	61	15500	181245
United States	1960	72000	1028000	370	2
Venezuela	1961	40	13	1100000	486317
Vietnam, Dem. Rep.	1952	200	800	33	33
Vietnam, Rep. of	1952	...	...	1000	2994
Yugoslavia	1967	9	310	15	...
Zaire	1956	5	68	319	1062
Zambia	1967	85	30	73	106
				115	218

Note: Measured reserves represent the total amounts occurring within certain limits (seams containing not less than 30 cm of coal and situated not more than 1200 m below the surface) and with respect to which there exist reliable data of thickness and extent of seams.

Inferred and indicated reserves represent reserves, in addition to the measured reserves and within the limits of thickness and depth of seam specified for measured reserves, as may be reasonably assumed to exist from incomplete investigations or from relation to measured reserves exist.

Total reserves represent the aggregate of the measured, indicated, and inferred reserves.

Production data relate to all grades of anthracite and bituminous coal (including semi-bituminous), but exclude lignite and brown coal, except where otherwise stated.

Source: World Power Conference, Survey of Energy Resources, 1981, London.

TABLE A.2 Lignite and Brown, Coal Reserves and Production

Country	Reserves (Million tonnes)			Production (Thousand tonnes)	
	Date	Measured	Inferred	Average 1964-68	1972
World Total	...	...	...	2041400	737200
Albania	...	...	...	...	806200
Australia	1966	48400	47200	391	...
Austria	1966	109	34	95600	21913
Bulgaria	1965	1117	...	143	3756
Burma	1951	...	...	1117	25583
Canada	1960	12250	11850	265	...
China	1966	355	5010	24100	1899
Czechoslovakia	1956	...	...	5365	70
Denmark	1966	8234	1623	700	(...)
France	1967	50	...	9857	73835
German Dem. Rep.	1967	...	...	50	1674
Germany, Fed. Rep. of	1967	...	...	30	2729
Greece	1952-	62000	...	30000	249189
Hungary	1961	908	667	...	101844
India	1966	...	...	1575	5017
Indonesia	1949-	...	...	5679	11318
Italy	1967	2000	355	2063	25287
Japan	1955	238	1495	524	22171
Korea, Dem.	...	...	...	1733	2698
Korea, Rep. of	1962	2	3	...	3900
Madagascar	1963	18	14	...	...
Mongolia	...	...	...	32	...
New Zealand	1967	17	369	1046	2147
Nigeria	1962	...	...	386	1949
Pakistan	1966	22	258	73	1647
Peru	1966	...	4630	280	...
Philippines	1965	74	14	4630	...
Poland	1967	6449	8413	88	...
Portugal	1960	26	...	14862	23643
Romania	1966	...	...	62	38221
Spain	1960	780	...	1367	62
Thailand	1967	235	...	6869	16547
Turkey	1957	251	1630	2706	3070
USSR	1966	104354	1302036	...	208
Ukrainian SSR	...	...	...	1881	345
United States	1960	9400	396600	142379	5336
Yugoslavia	1966	11506	15094	11089	152467
				11664	11664
				3480	6169
				27130	30341

Note: Measured reserves represent the total amounts occurring within certain limits (seams containing not less than 30 cm of lignite or brown coal and situated not more than 500 m below the surface) and with respect to which there exist reliable data of thickness and extent of seams.

Inferred and indicated reserves represent reserves, in addition to the measured reserves and within the limits of thickness and depth of seam specified for measured reserves, those which may be reasonably assumed to exist.

Total reserves represent the aggregate of the measured, indicated, and inferred reserves.

Source: World Power Conference, Survey of Energy Sources, 1968 (London).

TABLE A.3 Crude Petroleum, Reserves and Production

Country	Specific gravity	Reserves (Million tonnes)	Production (Thousand tonnes) Average 1964-68	1972
World Total	...	76800	1649200	2527400
Albania	0.94	13	918	1569
Algeria	0.797	1235	33216	50477
Angola	0.89	174	696	7055
Argentina	0.878	344	15146	22130
Australia	0.846	208	736	16118
Austria	0.90	26	2737	2478
Bahrain	0.86	70	3133	3508
Bolivia	0.80	28	1076	2030
Brazil	0.82	104	5858	8179
Brunel	0.84	240	4650	8823
Bulgaria	0.86	38	353	248
Burma	0.89	5	637	968
Canada	0.847	1080	43524	72997
Chile	0.81	16	1693	1613
China	0.86	1709	11500	28600
Colombia	0.89	226	9454	10134
Congo	0.84	67	62	336
Cuba	0.95	...	95	117
Czechoslovakia	0.93	...	196	191
Denmark	0.82	33	...	73
Ecuador	0.88	834	322	4016
Egypt	0.87	531	6650	10630
France	0.86	13	2857	1484
Gabon	0.87	138	2371	6304
Germany, Fed Rep. of	0.87	71	7867	7098
Hungary	0.91	30	1761	1977
India	0.83	90	4280	7486
Indonesia	0.862	1466	24955	54080
West Iran	0.79	...	74	...
Iran	0.861	8515	111280	248498
Iraq	0.845	4433	65544	71125
Israel	0.87	0	798	6048
Italy	0.92	35	1949	1152
Japan	0.86	3	736	711
Kuwait	0.866	10197	113477	151097
Libyan Arab Rep.	0.831	3184	76365	106394
Malaysia	0.82	196	79	432
Mexico	0.864	389	17889	22163
Mongolia	0.86	...	12	...
Morocco	0.83	0	103	28
Netherlands	0.92	39	2289	1597
Neutral Zone	0.867	1861	20744	28610
New Zealand	0.784	31	0	139
Nigeria	0.863	1729	12887	90914
Norway	0.845	462	...	1626
Oman	0.86	687	2938	13940

(Cont'd)

TABLE A.3 (Cont'd)

Country	Specific gravity	Reserves (Million tonnes)	Production (Thousand tonnes) Average 1964-68	1972
Pakistan	0.86	5	524	455
Peru	0.85	68	3262	3194
Poland	0.85	7	389	347
Qatar	0.837	776	13344	28493
Romania	0.84	198	12857	14128
Saudi Arabia	0.856	18658	115319	285683
Spain	0.84	9	48	143
Sweden	0.97	...	33	...
Syrian Arab Republic	0.91	182	207	5862
Thailand	0.86	...	2	13
Trinidad and Tobago	0.89	223	8068	7246
Tunisia	0.82	58	1241	3975
Turkey	0.88	20	2070	3410
USSR	...	5716	265767	400440
Ukrainian SSR	...	(...)	(9123)	(14500)
Byelorussian SSR	...	(...)	(556)	(5846)
United Arab Emirates	0.826	2654	16397	58140
United Kingdom	0.86	716	92	83
United States	0.85	4899	411037	466956
Venezuela	0.897	1978	182355	168066
Yugoslavia	0.85	48	2190	3200

Note: Reserves represent the aggregate amount of crude petroleum remaining in the ground which geological and engineering information indicates, with reasonable certainty, to be recoverable in the future from known oil reservoirs, under existing economic and operating conditions.

Source: Based on World Oil (Houston, Texas) data.

TABLE A.4 Natural Gas Reserves and Production
Gas from: (A) Gas and petroleum fields, (B) coal mines.

Country	Code	Kilocalories per cubic metre	Reserves (Thousand million cubic metres)	Production (Million cubic metres)	
				Average 1964-68	1972
World Total			1972	1964-68	1972
Afghanistan	A	...	54100	765700	1204000
Algeria	A	...	...	387	2894
Angola	A	...	3964	1866	...
Argentina	A	...	40	...	...
Australia	A	8400-9300	206	4538	6183
Austria	A	8900	1069	4	2628
Bahrain	A	9600	16	1758	1963
Barbados	A	...	24	70	...
Belgium	A	8900-9040	...	3	2
Bolivia	B	8500	...	68	52
Brazil	A	...	139	85	...
Brunel	A	8600-9600	26	773	1242
Bulgaria	A	9920	708	203	453
Burma	A	8400	28	203	220
Canada	A	...	3	6	17
Chile	A	9210	1499	38971	82503
China	A	...	71	1745	4080
Colombia	A	10680	99	...	...
Congo	A	...	73	998	...
Czechoslovakia	A	...	85	...	15
	A	8000	11	806	1167
	B	8000	...	230	...
Denmark	...	...	...	...	...
Ecuador	A	...	14	...	...
Egypt	A	...	122	...	...
France	A	...	108	54	...
Gabon	A	9000	187	5309	...
German Democratic Republic	A	...	184	14	34
Germany, Federal Republic of	B	3300	...	121	...
	A	8450-10850	351	3629	16924
Hungary	B	8000	...	574	528
India	A	7930	119	1635	4110
Indonesia	A	...	44	193	693
Iran	A	...	156	2885	4126
Iraq	A	8000-8800	5656	1369	17185
Israel	A	...	566	514	...
Italy	A	9250	1	89	124
Japan	A	8650	170	8791	14142
	A	9500	8	1839	2428
	B	9100	...	265	265
Kuwait	A	...	...	2239	...
Libyan Arab Republic	A	...	1090	...	7800
Mexico	A	...	794	...	18694
Morocco	A	8700	305	15049	52
	A	...	0	12	...

(Contd)

TABLE A.4 (Contd)

Country	Code	Kilocalories per cubic metre	Reserves (Thousand million cubic metres)	Production (Million cubic metres)	
				Average 1964-68	1972
Netherlands	A	8420	2209	5387	5385
Neutral Zone	B	4160-4460	...	64	35
New Zealand	A	...	198	230	...
Nigeria	A	10145	142	...	222
Norway	A	...	1161	131	159
Oman	A	...	439	...	...
Pakistan	A	...	54	...	...
Pera	A	8675	547	2042	3795
Peru	A	8900	74	449	...
Poland	A	9000	85	1529	...
	B	9000	...	93	5823
Qatar	A	...	229	199	...
Romania	A	...	250	17872	26212
Rwanda	A	9500-10600	...	1	1
Saudi Arabia	A	...	1340	1300	...
Spain	A	...	14	4	...
Trinidad and Tobago	A	8900	139	1352	1618
Tunisia	A	11000	43	8	20
Turkey	A	...	9	...	...
USSR	A	10150-10970	18633	141148	221386
Ukrainian SSR	A	9500	...	43402	67236
United Arab Emirates	A	...	335	...	...
United Kingdom	A	10000	1303	503	26571
	B	8898	...	177	127
United States	A	9211	7535	488214	638030
Venezuela	A	10265	1165	6966	9468
Yugoslavia	A	7200-9700	44	410	1242

Note: Reserves represent the aggregate amount of natural gas within the reporting country that have been proved by surveying, drilling, or other recognized methods of investigation, and would be in the form of gas if released from the earth, but excludes liquids recoverable from gas.

Production data relate, as far as possible, to natural gas (consisting primarily of hydrocarbons) actually collected and utilized as a fuel or as raw material and obtained from (i) gas fields and petroleum fields, and (ii) coal mines. Unless otherwise stated, the series exclude the gases used for stabilizing the pressure in the fields, as well as the gas as flared, vented or wasted.

Source: Based on World Oil (Houston, Texas) data.

TABLE A.5 Uranium (U), Resources and Production

Country	Resources as on January 1973					Production (tonnes)				
	1964	1965	1966	1967	1968	1967	1968	1972	1972	1972
World Total	868800	20009	15768	14987	15649	17448	19185			
Argentina	9200	29	20	20	20	36	25			
Australia	71000	285	285	254	254	254	254			
Brazil	2500	...	...	...	...	...	...
Canada	185000	5605	3418	3025	2876	2847	3768			
Central African Republic	8000	...	...	...	...	...	...
France	36600	1024	1093	1186	1043	1018	1213			
Gabon	20000	451	557	474	481	450	210			
Greenland	5600	...	...	...	...	...	...
Italy	1200	...	...	...	...	...	...
Japan	2800	...	...	...	...	...	...
Mexico	1000	...	...	...	...	...	...
Niger	40000	...	...	...	...	...	...
Portugal	6400	15	32	36	81	81	81			
South Africa	202000	3419	2293	2528	2585	2987	3077			
Spain	8500	59	52	51	51	46	60			
Sweden	...	8	15	38	59	59	7			
Turkey	2200	...	...	...	...	...	...
United States	259000	9114	8033	7375	8199	9670	10514			
Yugoslavia	6000	...	...	...	...	...	...
Zaire	1800	...	...	...	...	...	...

Source: Nuclear Energy Agency of OECD and International Atomic Energy Agency.

TABLE A.6 Thermodynamic Physical and Combustion Properties

Group Name	Formula	Molecular weight	Density g/ml at 15.6°C	Specific Gravity at 15.6°C	Freezing point °C	Bolling point at 1 atm °C	R _{ovis} (atm)	Free (°C)
Methane	CH ₄	16.04	...	...	-182.5	-161.6	45.8	-82.3
Ethane	C ₂ H ₆	30.07	...	...	-183.2	-88.6	48.2	33.3
Propane	C ₃ H ₈	44.09	.507	.508	-187.6	-42.1	42.0	96.7
2-Methyl propane	C ₄ H ₁₀	58.12	.582	.584	-138.3	-0.54	37.5	151.7
(iso butane)	C ₄ H ₁₀	58.12	.56	.563	-159.8	-11.7	36.0	135.0
2-Pentane	C ₅ H ₁₂	72.15	.629	.631	-189.7	+36.1	33.3	196.7
butane	C ₄ H ₁₀	58.12	.623	.625	-159.9	27.9	32.9	191.1
n-Hexane	C ₆ H ₁₄	86.17	.662	.664	-94	68.7	29.9	235.0
2,2-Dimethyl butane	C ₆ H ₁₄	86.17	.652	.654	-98.2	49.7	—	266.6
n-Heptane	C ₇ H ₁₆	100.20	.686	.688	-90.5	98.4	27.0	295.5
2,2,4-Trimethyl pentane	C ₇ H ₁₆	114.22	.705	.707	-56.8	125.6	24.6	...
2,2,3-Trimethyl pentane	C ₇ H ₁₆	114.22	.717	.720	-12.2	109.8	118.5	...
3-Ethyl hexane	C ₇ H ₁₆	114.22	.715	.718	—	150.8	150.8	...
n-Nonane	C ₉ H ₂₀	128.25	.72	.722	-53.6	150.8	150.8	...
Hexadecane (cetane)	C ₁₆ H ₃₄	226.4	.767	.7740	-18.1	280	280	...

(Contd)

TABLE A.6 (Contd)

Formula	Enthalpy of combustion kcal/g mol		Enthalpy of formation kcal/g mol of fuel	Reid vapour pressure at 37.8 °C, kg/cm ²	Flammability limit (with air) at 1 atm (% by volume)		Theo. A/F (g air/g fuel)	Theo. A/F (g mol air/g mol fuel)
	Upper	Lower			Upper	Lower		
	11	12	13	14	15	16		
CH ₄	212.8	192.0	-17.9	...	15.00	5.3	17.13	9.45
C ₂ H ₆	372.8	340.0	-20.5	...	12.50	3.00	15.99	16.55
C ₂ H ₈	530.6	488.0	-24.8	...	9.35	2.12	15.58	23.65
C ₄ H ₁₀	688.0	635.5	-30.2	3.52	8.41	1.86	15.37	30.08
C ₄ H ₁₂	686.3	634.0	-31.4	5.27	8.44	1.80	15.37	30.08
C ₅ H ₁₂	845.2	782.2	-35.0	1.09	7.80	1.40	15.23	37.90
C ₅ H ₁₄	844.0	781.0	-36.9	1.43	7.60	1.32	15.23	37.90
C ₆ H ₁₄	1003.0	926.5	-39.9	0.344	7.40	1.18	15.15	45.00
C ₆ H ₁₆	998.0	924.5	-44.3	0.523	...	...	15.15	45.00
C ₇ H ₁₆	1160.0	1076.0	-44.9	0.112	6.70	1.10	15.08	52.00
C ₈ H ₁₈	1317.5	1222.0	-49.8	...	6.00	0.95	15.03	59.30
C ₈ H ₂₀	1315.0	1221.0	-53.5	0.119	...	...	15.03	59.30
C ₉ H ₂₀	1315.1	1221.1	-52.5	...	...	...	15.03	59.30
C ₉ H ₂₂	1316.1	1222.1	-50.4	...	...	...	15.03	59.30
C ₉ H ₂₄	1473.4	1368.4	...	...	...	0.83	15.00	66.40
C ₁₀ H ₂₄	2570.0	2391.5	...	...	...	...	14.90	116.50

(Contd)

TABLE A.6 (Contd)

Formula	(h _{fg}) _{25°C} kcal/g mol	(h _{fg}) _{1 atm} kcal/g mol	Self-ignition temp °C	Critical compression ratio	Octane number	Cetane number
	17	18	19	20	21	22
CH ₄	...	1.95	730.0	12.6	110	
C ₂ H ₆	...	3.51	565.6	12.4	104	
C ₂ H ₈	3.60	4.44	535.0	12.2	100	
C ₄ H ₁₀	5.03	5.35	516.2	5.5	92	
C ₄ H ₁₂	4.54	5.08	...	8.0	99	
C ₅ H ₁₂	6.32	6.15	500.6	4.0	61	
C ₅ H ₁₄	5.88	5.83	...	5.7	90	
C ₆ H ₁₄	7.55	6.90	487.2	3.3	25	
C ₆ H ₁₆	6.66	6.28	...	...	...
C ₇ H ₁₆	8.70	7.57	478.4	3.0	0	57
C ₈ H ₁₈	9.91	8.35	471.1	2.9	-17	
C ₈ H ₂₀	8.42	7.4	732.2	7.3	100	
C ₈ H ₂₂	8.84	7.68	...	...	...
C ₉ H ₂₀	9.48	8.18	...	...	...
C ₉ H ₂₂	11.10	9.02	466.2	...	-45	
C ₁₀ H ₂₄	...	...	...	...	...	100

(Contd)

TABLE A.6 (Contd)

Formula	11	12	13	14	15	16
C_8H_8	337.2	+12.5	...	28.60	2.75	14.69
C_8H_8	492.0	+4.87	...	11.10	2.00	14.69
C_8H_8	649.7	+0.28	...	9.95	1.65	14.69
C_8H_{10}	1279.1	-19.8	...	...	...	14.69
C_8H_{10}	793.4	...	...	...	...	14.69
C_8H_{10}	944.8	...	...	0.70	...	14.69
C_8H_{10}	789.1	...	...	7.75	1.26	14.69
C_8H_{10}	943.6	+19.8	0.224	7.10	1.40	13.80
C_8H_{10}	1098.5	+11.95	0.077	6.75	1.27	13.40
C_8H_{10}	310.6	-4.54	0.245	6.00	1.00	13.58
C_8H_{10}	468.0	+54.9	...	80.0	2.5	13.18
C_8H_{10}	182.6	-44.3	...	...	...	13.71
C_8H_{10}	336.8	-48.1	...	36.5	6.72	6.4
C_8H_{10}	483.0	-56.2	...	18.95	3.28	9.0
C_8H_{10}	441.0	...	...	13.5	2.1	10.5

(Contd)

TABLE A.6 (Contd)

Formula	1	2	3	4	5	6	7	8	9	10
Ethylene (ethene)	C_2H_4	28.05	...	...	...	...	-169.2	-159.3	50.0	14.4
Propylene (propene)	C_3H_6	42.08	-52	-52	-52	-52	-185.2	-47.7	45.6	91.7
1-Butene	C_4H_8	56.10	60	60	60	60	-185.3	6.7	39.7	146.7
2-Occene	$H_2C=C_2$	112.21	-718	-718	-718	-718	-102.4	-121.3	...	...
Cyclo- pentane	C_5H_{10}	70.13	748	748	748	748	-93.8	49.3	...	...
Cyclo- hexane	C_6H_{12}	84.15	780	780	780	780	+6.55	80.8	40.0	280
Bunzene	C_6H_6	78.11	882	882	882	882	+5.5	80.2	48.6	289.4
Methyl benzene	C_7H_8	92.13	870	870	870	870	-9.5	110.7	41.6	321.1
1,2-Dimethyl benzene	C_8H_{10}	106.16	882	882	882	882	-25.2	144.4	...	...
Acetylene (ethyne)	C_2H_2	26.04	...	...	...	...	-80.1	...	...	...
Methyl acetylene (propyne)	C_3H_4	40.06	...	...	...	...	-23.2	...	...	...
Methyl alcohol	CH_3O	32.0	79	79	79	79	-97.8	65.0	77.8	...
Ethyl alcohol	C_2H_5O	46.0	783	783	783	783	-117.2	...	...	...
Propyl alcohol	C_3H_7O	60.0	796	796	796	796	...	97.8	...	...

(Contd)

TABLE A.6 (Contd)

Formula	* 17	18	19	20	21	22
C ₂ H ₄	...	3.35	...	...	...	...
C ₃ H ₆	...	2.76	...	10.6	85	...
C ₄ H ₈	4.87	5.24	...	7.1	80	...
C ₅ H ₁₀	...	...	...	...	...	...
C ₆ H ₁₂	6.80	6.53	...	12.4	83	...
C ₇ H ₁₄	7.88	7.16	...	4.9	77	...
C ₈ H ₁₆	8.08	7.53	740.00	15	100	...
C ₉ H ₁₈	9.08	8.0	811.00	15	104	...
C ₁₀ H ₂₀	10.40	8.8	...	15.5	105	...
C ₈ H ₂	...	...	...	...	...	...
C ₈ H ₄	...	...	...	...	...	...
CH ₂ O	8.92	...	...	...	98	...
C ₂ H ₂ O	10.01	...	...	...	99	...
C ₂ H ₄ O	9.84	...	...	...	...	...

TABLE A.7 Requirements of Motor Gasolines

Sr. No.	Characteristics	Requirements	
		83 Octane	93 Octane
(i)	Colour, visual	Orange	Red
(ii)	Copper-strip corrosion for 3 hours at 50°C	Not worse than No. 1	Not worse than No. 1
(iii)	Density at 15°C	Not limited but to be reported	Not limited but to be reported
(iv)	Distillation:		
	(a) Initial boiling point	Not limited but to be reported	
	(b) Recovery upto 70°C, % by volume, min	10	10
	(c) Recovery upto 125°C, % by volume, min	50	50
	(d) Recovery upto 100°C, % by volume, min	90	90
	(e) Final boiling point, max	215°C	215°C
	(f) Residue, % by volume, max	2	2
(v)	Octane number (research method), min	83	93
(vi)	Oxidation, stability, in minutes, min	360	360
(vii)	Residue on evaporation, mg/100 ml, max	4.0	4.0
(viii)	Sulphur, total % by weight, max	0.25	0.20
(ix)	Lead content (as Pb), g/l, max	0.56	0.80
(x)	Reid vapour pressure at 38°C, kgf/cm ² , max	0.70	0.70

Source: IS 2716-1971.

TABLE A.8 Requirements for Aviation Gasoline

Sr. No.	Characteristics	Requirement for			
		Grade 73	Grade 80	Grade 91/96	Grade 100/130 115/145
(i)	Reid vapour pressure at 38°C, g/cm ²		385 to 490		
(ii)	Distillation:				
	(a) Initial boiling point		not limited but to be reported		
	(b) % by volume evaporated upto 75°C		10 to 40		
	(c) % by volume evaporated upto 105°C, min		50		
	(d) % by volume evaporated upto 135°C, min		90		
	(e) Final boiling point, max		170°C		
	(f) Sum of individual temperatures of the 10 to 50% by volume evaporated points, min		135°C		
	(g) Residue, % by volume, max		1.5		
	(h) Loss, % by volume, max		1.5		
(iii)	Freezing point, max		60°C		
(iv)	Residue on evaporation (air jet) mg/100 ml, max		3		
(v)	Oxidation stability (16 hour ageing)				
	(a) Gum, mg/100 ml, max		6		
	(b) Precipitate, mg/100 ml, max		2		
(vi)	Density at 15°C		not limited but to be reported		
(vii)	Sulphur, total % by weight, max		0.05		
(viii)	Copper-strip corrosion for 2 hr at 100°C		Not worse than No. 1		
(ix)	Water reaction:				
	(a) Volume change in ml of aqueous layer, max		2		
	(b) Separation		Sharp separation, no emulsion or precipitate within or upon either layer		
(x)	(c) Interface condition		Not worse than rating 2		
	Calorific value, net, cal/g, min (see Note 1)	10,390	10,390	10,390	10,500
	or				
	Product of API gravity and aniline point (°F), min (see Note 2)	7500	7500	7500	9000

(Contd)

TABLE A.8 (Contd)

Sr. No.	Characteristics	Requirement for			
		Grade 73	Grade 80	Grade 91/96	Grade 100/130 115/145
(xi)	Tetraethyl lead, ml/l at 15°C, max.	Zero	Zero	1.22	1.22
(xii)	Knock rating (see Note 3)				
	(a) Lean mixture, min				
	1. Motor method or	73	80 ON	90 ON	99 ON
	2. Aviation method or	...	...	91 ON	100 ON 115 PN
	3. Extended motor method	...	...	...	116 PN
	(b) Rich mixture, min	...	...	96 ON	130 ON 145 PN
(xiii)	Aromatic content, % by volume, min	...	...	...	5.0

Note 1: The gross calorific value shall be corrected to 25°C by adding to it a quantity equal to 1.6 (T-25) where T is the final temperature in °C. The net calorific value shall then be calculated using the following equation:

$$\text{Net cal/g} = 2395 + 0.7195 \text{ times gross cal/g}$$

Note 2: Convert the aniline point determined in °C to °F. Also find out the API gravity at 60°F from density figure at 15°C, using the ASTM/IP Table No. 3. Alternatively, calculate the API gravity from the sp. gr. in accordance with the formula:

$$\text{Degree API} = \frac{141.5}{\text{sp gr at } 15.56^\circ\text{C}} - 131.5$$

Note 3: As determined by the standard methods specified except that
 (a) knock ratings below 100 shall be reported to the nearest 0.1 octane number (ON), and
 (b) knock ratings above 100 shall be determined to the nearest 0.01 ml of TEL/3.78 litres and reported to the nearest 0.1 performance number (PN).

TABLE A.9 Requirements for Aviation Turbine Fuel, Kerosene Type

Sr. No.	Characteristics	Requirement for	
		Grade K-40	Grade K-50
(i)	Acidity, inorganic	nil	nil
(ii)	Aromatic, % by volume, max	20	20
(iii)	Bromine number, max	5	...
	Alternatively		
	Olefin content, % by volume, max	5	5
(iv)	Colour Lovibond, max	4.0	...
(v)	Copper-strip corrosion for 2 hours at 100°C	Not worse than No. 1	
(vi)	Distillation:		
	(a) Initial boiling point °C	Not limited but to be reported	
	(b) Recovery temperature for 20% by volume, °C	-----do-----	
	(c) Recovery upto 200°C, % by volume, min	20	20
	(d) Recovery temperature for 50% by volume, °C	Not limited but to be reported	
	(e) Recovery temperature for 90% by volume, °C	-----do-----	
	(f) Final boiling point, °C max	300	300
	(g) Residue, percent by volume, max	2.0	1.5
	(h) Loss, percent by volume, max	1.5	1.5
(vii)	Flash point (Abel) °C min	38	38
(viii)	Freezing point, °C max	-40	-50
(ix)	Residue on evaporation mg/100 ml, max	3	7
(x)	Oxidation stability (16 hr ageing):		
	(a) Gum content, mg/100 ml, max	6 total	14 total
	(b) Precipitate, mg/100 ml, max	To be reported separately.	
(xi)	Calorific value (net), cal/g, min	10165	10225
	Alternatively,		
	Product of API gravity and aniline point °F, min	4500	5250
(xii)	Density at 15°C g/ml	0.775 to 0.825	0.775 to 0.825
(xiii)	Sulphur, mercaptane, % by weight, max	0.005	0.001
	Alternatively, Doctor test	Negative	
(xiv)	Sulphur total, % by weight, max	0.02	0.02

(Contd)

TABLE A.9 (Contd)

Sr. No.	Characteristics	Requirement for	
		Grade K-40	Grade K-50
(xv)	Kinematic viscosity at -17.8°C in CS, max	6	6
(xvi)	Smoke point mm, min.	—	20
(xvii)	Water reaction:		
	(a) change in volume of layer, max	1 ml	—
	(b) separation	Sharp separation, no emulsion or precipitate within or upon either layer	
	(c) Interface rating, max	1 b	1 b
(xviii)	Water separator index modified, min	—	85
(xix)	Thermal stability		
	(a) change in pressure drop in 5 hr mm Hg, max	—	75
	(b) preheater deposit rating, max	—	less than 3
(xx)	Silver strip corrosion	Not exceeding 1	

Source: IS 1571-1967.

TABLE A.10 Requirements for Aviation Turbine Fuel. High Flash Point Type

Sr. No.	Characteristics	Requirement
(i)	Acidity, inorganic	Nil
(ii)	Aromatic, % by volume, max	25
(iii)	Olefin content, percent by volume, max	5
(iv)	Copper-strip corrosion for 2 hr at 100°C	Not worse than No. 1
(v)	Distillation:	
	(a) Initial boiling point °C	Not limited but to be reported
	(b) Fuel evaporation up to 204°C, % by volume, min	10
	(c) Recovery temperature for 20% by volume, °C	Not limited but to be reported
	(d) Recovery temperature for 50% by volume, °C	—do—
	(e) Recovery temperature for 90% by volume, °C	—do—
	(f) Final boiling point, max	288°C
	(g) Residue, percent by volume, max	1.5
	(h) Loss, percent by volume, max	1.5
(vi)	Flash point (Abel) °C, min	60°C
(vii)	Freezing point °C, max	—46°C
(viii)	Residue on evaporation, mg/100 ml, max	7
(ix)	Oxidation stability (16 hr ageing) total mg/100 ml, max	
(x)	Calorific value net, cal/g, min	14
	Alternatively, Product of API gravity and aniline point, °F min	10165
(xi)	Density at 150°C, gm/ml	4500
(xii)	Sulphur, mercaptane % by weight, max	0.788 to 0.845
	Alternatively by Doctor test	0.001
(xiii)	Sulphur total, % by weight, max	Negative
(xiv)	Kinematic viscosity at —45.4°C in CS, max	0.4
(xv)	Smoke point mm, min	16.5
(xvi)	Water reaction	20
	(a) Separation	Sharp separation, no emulsion or precipitate within or upon another layer
	(b) Interface rating, max	16
(xvii)	Water separator index, modified, min	85°
(xviii)	Thermal stability:	
	(a) Change in pressure drop in 5 hr, mm of Hg, max	75
	(b) preheater deposit rating, max	Less than 3

Source: IS 1587-1967.

TABLE A.11 Requirements for Kerosene

Sr. No.	Characteristics	Requirement for Grade SK
(i)	Acidity, inorganic	Nil
(ii)	Burning quality:	
	(a) Char value, mg/kg of oil consumed, max	20
	(b) Bloom on glass chimney	Not darker than gray
(iii)	Colour (Saybolt), min	10
(iv)	Distillation:	
	(a) Percent recovered below 200°C, min	20
	(b) Final boiling point, °C, max	300
(v)	Copper-strip corrosion for 3 hr at 50°C	Not worse than No. 1
(vi)	Flash point (Abel), °C, min	35
(vii)	Smoke point, mm, min	20
(viii)	Total, sulphur, % by mass, max	0.25

Source: IS 1959-1470

TABLE A.12 Requirements for Diesel Fuel

Sr. No.	Characteristics	HSD	Requirements LDO
(i)	Acidity, inorganic	Nil	Nil
(ii)	Acidity, total, mg of KOH/g, max	0.50	...
(iii)	Ash, percent by mass, max	0.01	0.02
(iv)	Carbon residue (Ramsbottom percent by mass, max	0.20	1.50
(v)	Cetane number, min	42	...
(vi)	Pour point, min	6°C	12°C for winter, 18°C for summer
(vii)	Copper strip corrosion for 3 hours at 100°C	Not worse than No. 1	Not worse than No. 2
(viii)	Distillation percent recovery at 366°C, min	90	...
(ix)	Flash point:		
	(a) Abel, °C, min	38	...
	(b) Pensky-Martens °C min	...	66
(x)	Kinematic viscosity, CS, at 38°C	2.0 to 7.5	2.5 to 15.7
(xi)	Sediment, percent by mass, max	1.05	0.10
(xii)	Water content, percent by volume, max	0.05	0.25
(xiii)	Total sediments, mg per 100 ml, max	1.0	...
(xiv)	Total sulphur, percent by mass, max	1.0	1.8

Source: IS 1960-1970

TABLE A.13 Requirements for Fuel Oils

Sr. No.	Characteristics	Requirement for		
		Grade LV	Grade MV	Grade HV
(i)	Acidity, inorganic	Nil	Nil	Nil
(ii)	Ash, percent by weight, max	0.1	0.1	0.1
(iii)	Flash point, pencky martens (closed) min	66°C	66°C	66°C
(iv)	Kinematic viscosity in centi-strokes at 50°C, max	80	125	370
(v)	Sediment, % by weight, max	0.25	0.25	0.25
(vi)	Sulphur, total, % by weight, max	3.5	4.0	4.5
(vii)	Water content, % by volume, max	1.0	1.0	1.0
(viii)	Gross calorific value in cal/g	Not limited but to be reported		

Source: IS 1593-1971.

TABLE A.14 Requirements for Liquefied Petroleum Gasoline

Sr. No.	Characteristics	Requirements		
		Commercial butane	Commercial butane-propane mixture	Commercial propane
(i)	Vapour pressure at 65°C kg/cm ² gauge	10 max	10 to 26	26 max
(ii)	Volatility evaporation temperature in °C for 95% by volume at 760 mm Hg pressure, max	2	2	-38
(iii)	Total volatile sulphur, % by weight, max	0.02	0.02	0.02
(iv)	Copper strip corrosion	Not worse than No. 1		
(v)	Hydrogen sulphide	Absent		
(vi)	Dryness	No free entrain water		
(vii)	Odour	Level 2		

Source: IS 4576-1968.

TABLE A.15 Enthalpy of Formation, ΔH_f° at 25°C and 1 ATM

Substance	Formula	Molecular weight	$\Delta H_f^\circ \times 10^{-3}$	
			kcal/kmol	kJ/kmol
Carbon	C(s)	12.01	0.0	0.0
Hydrogen	H ₂ (g)	2.018	0.0	0.0
Oxygen	O ₂ (g)	32.00	0.0	0.0
Carbon monoxide	CO(g)	28.01	-26.417	-110.578
Carbon dioxide	CO ₂ (g)	44.01	-94.154	-393.769
Water	H ₂ O(g)	18.02	-57.798	-241.997
Water	H ₂ O(l)	18.02	-68.317	-286.028
Hydrogen peroxide	H ₂ O ₂ (g)	34.02	-32.530	-136.187
Ammonia	NH ₃ (g)	17.04	-11.040	-46.218
Methane	CH ₄ (g)	16.04	-17.895	-74.920
Acetylene	C ₂ H ₂ (g)	26.04	+54.190	+226.878
Ethylene	C ₂ H ₄ (g)	28.05	+12.496	+52.312
Ethane	C ₂ H ₆ (g)	30.07	+20.236	+84.713
Propylene	C ₃ H ₆ (g)	42.08	+4.879	+20.446
Propane	C ₃ H ₈ (g)	44.09	+24.820	+103.926
n-Butane	C ₄ H ₁₀ (g)	58.12	-30.150	-126.232
n-Pentane	C ₅ H ₁₂ (g)	72.15	-35.000	-146.538
n-Hexane	C ₆ H ₁₄ (g)	86.17	-39.960	-167.309
n-Heptane	C ₇ H ₁₆ (g)	100.20	-44.890	-187.941
n-Octane	C ₈ H ₁₈ (g)	114.22	-49.820	-208.596
Benzene	C ₆ H ₆ (g)	78.11	+19.820	+82.992
Toluene	C ₇ H ₈ (g)	92.13	+11.950	+50.032
Methyl alcohol	CH ₃ OH(g)	32.05	-48.080	-201.292
Ethyl alcohol	C ₂ H ₅ OH(g)	46.07	-56.240	-235.461
Oxygen	O(g)	16.00	+59.559	+249.370
Hydrogen	H(g)	1.009	+52.102	+218.132
Nitrogen	N(g)	14.004	+112.965	+472.969
Fluorine	F(g)	19.00	+18.860	+78.968
Hydroxyl	OH(g)	17.01	+9.330	+39.054
Hydrogen fluoride	HF(g)	20.01	-64.800	-271.305

TABLE A.16 Enthalpy of Combustion, ΔH_R° and Enthalpy of Vaporization, h_{fg} at 25°C and 1 ATM
Water appears as liquid in the products of the combustion.

Substance	Formula	ΔH_R° kcal/kmol	h_{fg} kcal/kmol	ΔH_R° kJ/kmol	h_{fg} kJ/kmol
Hydrogen	$\text{H}_2(\text{g})$	-68377		-286028	
Carbon	$\text{C}(\text{s})$	-94094		-393769	
Carbon monoxide	$\text{CO}(\text{g})$	-67636		-283191	
Methane	$\text{CH}_4(\text{g})$	-212800		-890951	
Acetylene	$\text{C}_2\text{H}_2(\text{g})$	-310600		-1308513	
Ethylene	$\text{C}_2\text{H}_4(\text{g})$	-337230		-1411905	
Ethane	$\text{C}_2\text{H}_6(\text{g})$	-372820		-1569932	
Propylene	$\text{C}_3\text{H}_6(\text{g})$	-491990		-2059859	
Propane	$\text{C}_3\text{H}_8(\text{g})$	-530600	3599	-2221493	15072
n-Butane	$\text{C}_4\text{H}_{10}(\text{g})$	-687650	5032	-279123	21074
n-Pentane	$\text{C}_5\text{H}_{12}(\text{g})$	-845160	6310	-3538544	26423
n-Hexane	$\text{C}_6\text{H}_{14}(\text{g})$	-1002570	7537	-4197500	31548
n-Heptane	$\text{C}_7\text{H}_{16}(\text{g})$	-1169010	8728	-4856688	36548
n-Octane	$\text{C}_8\text{H}_{18}(\text{g})$	-1317450	9906	-5515876	41484
Benzene	$\text{C}_6\text{H}_6(\text{g})$	-789080	8083	-3303618	33848
Toluene	$\text{C}_7\text{H}_8(\text{g})$	-943580	9540	-3950478	39951
Methyl alcohol	$\text{CH}_3\text{OH}(\text{g})$	-182610	8938	-764556	37430
Ethyl alcohol	$\text{C}_2\text{H}_5\text{OH}(\text{g})$	-336820	10118	-1410207	42370

TABLE A.17 Equilibrium Constants, K_p of Various Reactions

Values are given as $\log_{10} K_p$. For the reaction $aA + bB \rightleftharpoons mM + nN$ the equilibrium constant is defined by $K_p = \frac{P_M^m P_N^n}{P_A^a P_B^b}$

Temperature	$\text{H}_2 \rightleftharpoons 2\text{H}$	$\text{O}_2 \rightleftharpoons 2\text{O}$	$\text{N}_2 \rightleftharpoons 2\text{N}$	$\text{H}_2\text{O}(\text{g}) \rightleftharpoons \text{H}_2 + \frac{1}{2}\text{O}_2$	$\text{H}_2\text{O}(\text{g}) \rightleftharpoons \text{OH} + \frac{1}{2}\text{H}_2$	$\text{CO}_2 \rightleftharpoons \text{CO} + \frac{1}{2}\text{O}_2$	$\text{CO}_2 + \frac{1}{2}\text{H}_2 \rightleftharpoons \text{CO} + \frac{1}{2}\text{H}_2\text{O}$
298	-71.228	-81.208	-159.600	-40.048	-46.054	-45.066	-15.171
500	-40.318	-45.880	-92.672	-22.886	-26.130	-25.025	-8.783
1000	-17.292	-19.614	-43.056	-10.062	-11.280	-10.221	-4.062
1500	-9.514	-10.790	-26.434	-5.725	-6.284	-5.316	-2.487
1800	-6.896	-7.836	-20.874	-4.270	-4.613	-3.693	-1.962
2000	-5.582	-6.356	-18.092	-3.540	-3.776	-2.884	-1.699
2200	-4.502	-5.142	-15.810	-2.942	-3.091	-2.226	-1.484
2400	-3.600	-4.130	-13.908	-2.443	-2.520	-1.679	-1.305
2500	-3.202	-3.684	-13.070	-2.224	-2.270	-1.440	-1.227
2600	-2.836	-3.272	-12.298	-2.021	-2.038	-1.219	-1.154
2800	-2.178	-2.536	-10.914	-1.658	-1.624	-0.825	-1.025
3000	-1.606	-1.898	-9.716	-1.343	-1.265	-0.485	-0.913
3200	-1.106	-1.340	-8.664	-1.067	-0.951	-0.189	-0.815
3500	-0.462	-0.620	-7.312	-0.712	-0.547	+0.190	-0.690
4000	+0.400	+0.340	-5.504	+0.133	+0.308	+0.079	-0.397
4500	+1.074	+1.086	-2.962	+0.430	+0.741	+1.386	-0.296
5000	+1.612	+1.686					

TABLE A.18 Molar Heat Capacities for a Selection of Gases* according to the Equation $C_p = a + bT + cT^2 + dT^3$

Compound	Formula	a	10 ⁴ b	10 ⁶ c	10 ⁹ d	Valid, K
Ammonia	NH ₃	27.55	2.563	0.9900	-6.686	273-1500
Benzene	C ₆ H ₆	-36.19	48.44	-31.55	77.57	273-1500
Carbon monoxide	CO	27.11	0.655	-0.1000	...	273-3800
Carbon dioxide	CO ₂	22.24	5.979	-3.498	7.464	273-1800
Ethane	C ₂ H ₆	6.895	17.25	6.402	7.280	273-1500
Ethanol	C ₂ H ₅ OH	19.9	20.95	-10.372	20.04	273-1500
Ethylene	C ₂ H ₄	3.95	15.63	-8.339	17.66	273-1500
Hydrogen fluoride	H ₂	29.09	-0.1916	0.4000	-0.870	273-1800
Hydrogen chloride	HF	30.13	-0.494	0.6594	-1.573	273-2000
Hydrogen iodide	HI	30.31	-0.761	1.326	-4.335	273-1500
Methane	CH ₄	19.87	5.021	1.268	-11.00	273-1500
Methyl chloride	CH ₃ Cl	12.76	10.86	-5.205	9.623	273-1500
Nitrogen	N ₂	27.32	0.6226	-0.0950	...	273-3800
Oxygen	O ₂	25.46	1.519	-0.7150	1.311	273-1800
Water	H ₂ O	32.22	0.1920	1.054	-3.594	273-1800

*Taken from Kobe, K. A., *Thermochemistry for the Petrochemical Industry*, Petroleum Refiner (November 1954). Units are in J/mol K.

TABLE A.19 Ideal Gas Enthalpy, Absolute Entropy, and Equilibrium Constant of Formation for Nitrogen, N₂*
ΔH_f⁰ = 0 kcal/kmol, 0 kJ/kmol

Temperature K	$h_f^0 - h_{f,0}^0$ kJ/kmol	S^0 kJ/kmol K	$\log_{10} K_p$	$h_f^0 - h_{f,0}^0$ kJ/kmol	S^0 kJ/kmol K
0	-2072	0	0.00	-8676	0
298	0	45.77		0	191.630
300	13	45.813		53	191.810
400	710	47.818		2973	200.204
500	1413	49.386		5915	206.770
600	2125	50.685		8897	212.208
700	2853	51.805		11944	216.901
800	3596	52.798		15056	221.055
900	4355	53.692		18234	224.798
1000	5129	54.507		21474	228.210
1100	5917	55.258		24774	231.354
1200	6718	55.955		28126	234.272
1300	7529	56.604		31522	236.990
1400	8350	57.212		34960	239.535
1500	9179	57.784		38430	241.930
1600	10015	58.334		42035	244.191
1700	10858	58.835		45459	246.330
1800	11707	59.330		49016	248.361
1900	12560	59.782		52586	250.295
2000	13418	60.222		56178	252.137
2100	14280	60.645		59788	253.896
2200	15146	61.045		63414	255.583
2300	16015	61.431		67052	257.199
2400	16886	61.802		70699	258.753
2500	17761	62.159		74362	260.247
2600	18638	62.503		78033	261.688
2700	19517	62.835		81715	263.078
2800	20398	63.155		85401	264.417
2900	21280	63.465		89095	265.715
3000	22165	63.765		92800	266.971
3200	23999	64.337		100227	269.366
3400	25719	64.877		107680	271.627
3600	27505	65.387		115158	273.762
3800	29295	65.871		122652	275.789
4000	31089	66.331		130163	277.715
4200	32888	66.770		137695	279.553
4400	34690	67.189		145240	281.307
4600	36496	67.591		152802	282.990
4800	38306	67.976		160380	284.602
5000	40119	68.346		167970	286.151

* Tables A.19 through A.28 with permission of the DOW Chemical Company, from JANAF Thermochemical Tables, Second Edition, 1971.

TABLE A.20 Ideal Gas Enthalpy, Absolute Entropy, and Equilibrium Constant of Formation for Diatomic Oxygen, O₂
 $\Delta H_f^\circ = 0$ kcal/kmol, 0 kJ/kmol

Temperature K	$h_f^\circ - h_{f,298}^\circ$ kcal/kmol	S kcal/kmol K	$\log_{10} K_p$	$h_f^\circ - h_{f,298}^\circ$ kJ/kmol	S° kJ/kmol K
0	-2075	0	0.00	-8688	0
298	0	49.004		0	205.170
300	13	49.047		53	205.350
400	724	51.091		3031	213.908
500	1455	52.722		6092	220.736
600	2210	54.098		9253	226.497
700	2988	55.279		12509	231.517
800	3786	56.361		15852	235.972
900	4600	57.320		19259	239.987
1000	5427	58.192		22723	243.638
1100	6266	58.991		26235	246.984
1200	7114	59.729		29784	250.073
1300	7971	60.415		33373	252.946
1400	8835	61.056		36990	255.626
1500	9706	61.656		40638	258.141
1600	10583	62.222		44308	260.511
1700	11465	62.757		48002	262.751
1800	12354	63.265		51723	264.878
1900	13249	63.749		55470	266.904
2000	14149	64.201		59239	268.834
2100	15054	64.652		63028	270.685
2200	15966	65.076		66847	272.460
2300	16882	65.483		70682	274.164
2400	17804	65.876		74541	275.810
2500	18732	66.254		78428	277.392
2600	19664	66.620		82329	278.925
2700	20602	66.974		86257	280.407
2800	21545	67.317		90205	281.843
2900	22493	67.650		94173	283.237
3000	23446	67.973		98164	284.589
3200	25365	68.592		106198	287.181
3400	27302	69.179		114309	289.639
3600	29254	69.737		122480	291.975
3800	31221	70.269		130717	294.202
4000	33201	70.776		139006	296.325
4200	35195	71.262		147345	298.360
4400	37196	71.728		155733	300.311
4600	39208	72.176		164155	302.186
4800	41229	72.606		172617	303.987
5000	43257	73.019		181109	306.017

TABLE A.21 Ideal Gas Enthalpy, Absolute Entropy, and Equilibrium Constant of Formation for Carbon Dioxide CO₂
 $\Delta H_f^\circ = -94154$ kcal/kmol = -393768 kJ/kmol

Temperature K	$h_f^\circ - h_{f,298}^\circ$ kcal/kmol	S° kcal/kmol K	$\log_{10} K_p$	$h_f^\circ - h_{f,298}^\circ$ kJ/kmol	S° kJ/kmol K
0	-2238	0	-	-9369	0
298	0	51.072	69.095	0	213.828
300	16	51.127	68.670	67.00	214.059
400	958	53.830	51.540	4010	225.376
500	1987	56.122	41.260	8320	234.972
600	3087	58.126	34.405	12926	243.362
700	4245	59.910	29.506	17733	250.831
800	5453	61.522	25.830	22830	257.580
900	6702	62.992	22.970	28061	263.735
1000	7984	64.344	20.680	33427	269.396
1100	9296	65.594	18.806	38921	274.629
1200	10632	66.756	17.243	44515	279.494
1300	11980	67.841	15.920	50190	280.037
1400	13362	68.859	14.785	55945	288.299
1500	14750	69.817	13.801	61755	292.310
1600	16152	70.722	12.940	67626	296.100
1700	17565	71.578	12.180	73541	299.683
1800	18987	72.391	11.504	79496	303.087
1900	20418	73.165	10.898	85485	306.327
2000	21857	73.903	10.353	91512	309.417
2100	23303	74.608	9.860	97564	312.369
2200	24755	75.284	9.411	103644	315.199
2300	26212	75.931	9.001	109745	317.908
2400	27674	76.554	8.625	115865	325.516
2500	29141	77.153	8.280	122008	322.448
2600	30613	77.730	7.960	128170	325.440
2700	32088	78.286	7.664	134345	327.786
2800	33567	78.824	7.388	140539	330.020
2900	35049	79.344	7.132	146743	332.197
3000	36535	79.848	6.892	152965	334.308
3200	39515	80.810	6.458	165441	338.355
3400	42507	81.717	6.074	177969	342.133
3600	45508	82.574	5.732	190532	345.721
3800	48518	83.388	5.425	203134	349.129
4000	51538	84.162	5.149	215778	352.369
4200	54566	84.901	4.898	228457	355.464
4400	57601	85.607	4.670	241164	358.419
4600	60664	86.284	4.406	253904	361.254
4800	63695	86.933	4.268	266678	363.971
5000	66753	87.557	4.091	279481	366.584

TABLE A.22 Ideal Gas Enthalpy, Absolute Entropy, and Equilibrium Constant of Formation for Carbon Monoxide, CO
 $\Delta H_f^\circ = -26417 \text{ kcal/kmol} = -110578 \text{ kJ/kmol}$

Temperature K	$h_T^\circ - h_{298}^\circ$ kcal/kmol	S° kcal/kmol K	$\log_{10} K_p$	$h_T^\circ - h_{298}^\circ$ kJ/kmol	S° kJ/kmol K
0	-2073	0	24.029	-8678	0
298	0	47.214	23.910	0	197.676
300	13	47.257	19.109	53	197.856
400	711	49.265	16.235	2977	206.263
500	1417	50.841	14.318	5934	212.861
600	2137	52.152	12.946	8948	218.350
700	2873	53.287	11.914	12028	223.102
800	3627	54.293	11.108	15186	227.314
900	4397	55.200	10.459	18416	231.111
1000	5183	56.028	9.926	21699	234.578
1100	5983	56.790	9.479	25049	237.768
1200	6794	57.496	9.099	28445	240.724
1300	7616	58.154	8.771	31887	243.479
1400	8446	58.769	8.485	35362	246.054
1500	9285	59.348	8.234	38874	248.478
1600	10130	60.009	8.011	42412	250.760
1700	10980	60.898	7.811	45971	252.920
1800	11836	61.363	7.631	49555	254.968
1900	12697	61.807	7.469	53161	256.916
2000	13561	62.230	7.321	56778	258.774
2100	14430	62.635	7.185	60416	260.545
2200	15301	63.024	7.061	64063	262.240
2300	16175	63.397	6.946	67721	263.869
2400	17052	63.756	6.840	71394	265.431
2500	17931	64.102	6.741	75074	266.934
2600	18812	64.435	6.649	78765	268.382
2700	19696	64.757	6.563	82464	269.776
2800	20582	65.069	6.483	86174	271.125
2900	21459	65.370	6.407	89886	272.431
3000	22357	65.645	6.269	93605	273.691
3200	24159	66.487	5.145	101065	276.099
3400	25927	66.999	6.034	108552	278.368
3600	27719	67.485	5.933	116053	280.511
3800	29516	67.946	5.842	123578	282.546
4000	31316	68.387	5.756	131144	284.476
4200	33121	68.807	5.679	138671	286.223
4400	34930	69.201	5.607	146245	288.081
4600	36741	69.596	5.540	153828	289.768
4800	38557	69.965	5.477	161431	291.385
5000	40376			169042	292.938

TABLE A.23 Ideal Gas Enthalpy, Absolute Entropy, and Equilibrium Constant of Formation for Water, H₂O
 $\Delta H_f^\circ = -57798 \text{ kcal/kmol} = -241997 \text{ kJ/kmol}$

Temperature K	$h_T^\circ - h_{298}^\circ$ kcal/kmol	S° kcal/kmol K	$\log_{10} K_p$	$h_T^\circ - h_{298}^\circ$ kJ/kmol	S° kJ/kmol K
0	-2367	0	40.048	-9911	0
298	0	45.106	39.786	0	188.850
300	15	45.155	29.240	63	189.055
400	825	47.486	22.886	3454	198.806
500	1654	49.334	18.633	6925	206.551
600	2509	50.891	15.583	10504	213.070
700	3390	52.249	13.289	14193	218.756
800	4300	53.464	11.498	18003	224.843
900	5240	54.570	10.062	21939	228.474
1000	6209	55.592	8.883	25995	232.753
1100	7210	56.545	7.899	30187	236.743
1200	8240	57.448	7.064	34499	240.494
1300	9298	58.288	6.347	38928	244.040
1400	10384	59.092	5.725	43475	247.406
1500	11493	59.859	5.180	48127	250.618
1600	12630	60.591	4.699	52879	253.682
1700	13787	61.293	4.270	57724	256.622
1800	14964	61.965	3.886	62651	259.435
1900	16160	62.612	3.540	67659	262.144
2000	17373	63.234	3.277	72736	264.748
2100	18602	63.834	2.942	77884	267.260
2200	19846	64.412	2.682	83092	269.680
2300	21103	64.971	2.443	88353	272.021
2400	22372	65.511	2.224	93650	274.281
2500	23653	66.034	2.021	99029	276.471
2600	24945	66.541	1.833	104440	278.594
2700	26246	67.032	1.658	109887	280.650
2800	27556	67.508	1.495	115372	282.642
2900	28875	67.971	1.343	120894	284.581
3000	30201	68.421	1.067	126446	286.465
3200	32776	70.102	0.824	137646	293.503
3400	35577	70.881	0.607	148955	296.765
3600	38300	71.622	0.413	160354	299.867
3800	41043	72.331	0.238	171838	302.835
4000	43805	73.008	0.079	183403	305.676
4200	46583	73.658	0.085	195033	308.391
4400	49375	74.281	0.197	206723	311.000
4600	52181	74.881	0.391	218472	313.302
4800	55000	75.459	0.430	230274	315.932
5000	57829			242118	

TABLE A.24 Ideal Gas Enthalpy, Absolute Entropy, and Equilibrium Constant of Formation for Diatomic Hydrogen H₂
 $\Delta H_f^\circ = 0$ kcal/kmol = 0 J/mol

Temperature K	$h_T^\circ - h_{298}^\circ$ kcal/kmol	S° kcal/kmol K	$\log_{10} K_p$	$h_T^\circ - h_{298}^\circ$ kJ/kmol	S° kJ/kmol K
0	-2024	0	0.000	-8474	0
298	0	31.208		0	130.662
300	13	31.251		53	130.842
400	707	33.247		2961	139.199
500	1406	34.806		5887	145.726
600	2106	36.082		8818	151.068
700	2808	37.165		11756	155.602
800	3514	38.107		14712	159.546
900	4226	38.946		17694	163.059
1000	4944	39.702		20699	166.224
1100	5670	40.394		23739	169.122
1200	6404	41.033		26812	171.797
1300	7148	41.628		29926	174.271
1400	7902	42.187		33085	176.629
1500	8668	42.716		36290	178.843
1600	9443	43.217		39549	180.941
1700	10233	43.695		42843	182.942
1800	11030	44.150		46180	184.847
1900	11836	44.586		49555	186.673
2000	12651	45.005		52965	188.432
2100	13475	45.506		56417	190.106
2200	14307	45.793		59901	191.726
2300	15146	46.166		63414	193.288
2400	15993	46.527		66959	194.799
2500	16848	46.875		70538	196.256
2600	17708	47.213		74159	197.671
2700	18575	47.540		77770	199.040
2800	19448	47.857		81424	200.368
2900	20326	48.166		85101	201.661
3000	20200	48.465		88802	202.913
3200	22992	49.040		96264	205.391
3400	24794	49.586		103807	207.607
3600	26616	50.107		111436	209.788
3800	28457	50.605		119145	211.873
4000	30317	51.082		126932	213.870
4200	32194	51.540		134789	215.788
4400	34088	51.980		142719	217.630
4600	35999	52.405		150720	219.409
4800	37926	52.815		158789	220.126
5000	39868	53.211		166918	222.784

TABLE A.25 Ideal Gas Enthalpy, Absolute Entropy, and Equilibrium Constant of Formation for Monoatomic Hydrogen, H
 $\Delta H_f^\circ = 52102$ kcal/kmol = 218132 kJ/kmol

Temperature K	$h_T^\circ - h_{298}^\circ$ kcal/kmol	S° kcal/kmol K	$\log_{10} K_p$	$h_T^\circ - h_{298}^\circ$ kJ/kmol	S° kJ/kmol K
0	-1481	0		-6201	0
298	0	27.392	-35.614	0	114.685
300	9	27.423	-35.378	37	114.815
400	506	28.852	-25.877	2119	120.798
500	1003	29.961	-20.159	4198	125.441
600	1500	30.867	-16.337	6280	129.234
700	1996	31.631	-13.599	8357	132.437
800	2493	32.296	-11.540	10437	135.217
900	2990	32.881	-9.934	12519	137.666
1000	3487	33.404	-8.646	14600	139.856
1100	3984	33.878	-7.590	16680	141.840
1200	4481	34.310	-6.707	18762	143.649
1300	4977	34.708	-5.958	20839	145.315
1400	5474	35.076	-5.315	22918	146.856
1500	5971	35.419	-4.757	25000	148.292
1600	6468	35.739	-4.267	27079	149.632
1700	6965	36.041	-3.834	29161	150.896
1800	7461	36.325	-3.448	31238	152.086
1900	7958	36.593	-3.102	33318	153.208
2000	8455	36.848	-2.791	35399	154.275
2100	8952	37.090	-2.508	37481	155.288
2200	9449	37.322	-2.251	39561	156.260
2300	9945	37.542	-2.016	41638	157.181
2400	10442	37.754	-1.800	43719	158.068
2500	10939	37.957	-1.601	45799	158.918
2600	11436	38.152	-1.418	47881	159.735
2700	11933	38.339	-1.247	49960	160.518
2800	12430	38.520	-1.089	52042	161.276
2900	12926	38.694	-0.941	54119	162.004
3000	13423	38.862	-0.803	56198	162.707
3200	14417	39.183	-0.553	60362	164.051
3400	15410	39.484	-0.332	64519	165.312
3600	16404	39.766	-0.135	68680	166.501
3800	17398	40.037	0.041	72841	167.627
4000	18391	40.292	0.200	77000	168.695
4200	19385	40.534	0.344	81161	169.708
4400	20377	40.765	0.476	85322	170.675
4600	21362	40.986	0.595	89481	171.600
4800	22350	41.198	0.705	93642	172.488
5000	23359	41.400	0.806	97799	173.334

TABLE A.26 Ideal Gas Enthalpy, Absolute Entropy, and Equilibrium Constant of Formation for Monoatomic Nitrogen, N
 $\Delta H_f^\circ = 112965 \text{ kcal/kmol} = 472969 \text{ kJ/kmol}$

Temperature K	$h_T^\circ - h_{298}^\circ$ kcal/kmol	S° kcal/kmol K	$\log_{10} K_p$	$h_T^\circ - h_{298}^\circ$ kJ/kmol	S° kJ/kmol K
0	-1401	0	-	-5866	0
298	0	36.614	-79.800	0	153.295
300	9	36.645	-79.289	37	153.425
400	506	38.074	-58.704	2119	159.408
500	1003	39.183	-46.336	4198	164.051
600	1500	40.089	-38.081	6280	167.845
700	1996	40.855	-32.177	8357	171.052
800	2493	41.518	-27.744	10437	173.828
900	2990	42.103	-24.292	12519	176.277
1000	3487	42.627	-21.528	14600	178.471
1100	3984	43.100	-19.265	16680	180.451
1200	4481	43.532	-17.377	18762	182.260
1300	4977	43.930	-15.778	20839	183.926
1400	5474	44.298	-14.406	22918	185.467
1500	5971	44.641	-13.217	25000	186.903
1600	6468	44.962	-12.175	27079	188.247
1700	6965	45.263	-11.258	29161	189.507
1800	7461	45.547	-10.437	31238	190.696
1900	7958	45.815	-9.705	33318	191.818
2000	8455	46.070	-9.046	35399	192.886
2100	8952	46.313	-8.449	37481	193.903
2200	9449	46.544	-7.905	39561	194.870
2300	9946	46.765	-7.409	41642	195.796
2400	10444	46.977	-6.954	43726	196.683
2500	10941	47.180	-6.535	45808	197.533
2600	11439	47.375	-6.149	47892	198.350
2700	11938	47.563	-5.790	49981	199.137
2800	12437	47.745	-5.457	52072	199.898
2900	12936	47.920	-5.147	54161	200.631
3000	13437	48.090	-4.858	56259	201.343
3200	14441	48.414	-4.332	60464	202.700
3400	15451	48.720	-3.868	64691	203.981
3600	16469	49.011	-3.455	68952	205.199
3800	17495	49.288	-3.085	73248	206.359
4000	18531	49.554	-2.752	77586	207.473
4200	19580	49.810	-2.450	81978	208.545
4400	20643	50.057	-2.176	86427	209.579
4600	21721	50.297	-1.924	90942	210.583
4800	22816	50.530	-1.694	95526	211.559
5000	23928	50.757	-1.481	100181	212.509

TABLE A.27 Ideal Gas Enthalpy, Absolute Entropy, and Equilibrium Constant of Formation for Monoatomic Oxygen, O
 $\Delta H_f^\circ = 59559 \text{ kcal/kmol} = 249370 \text{ kJ/kmol}$

Temperature K	$h_T^\circ - h_{298}^\circ$ kcal/kmol	S° kcal/kmol K	$\log_{10} K_p$	$h_T^\circ - h_{298}^\circ$ kJ/kmol	S° kJ/kmol K
0	-1608	0	-	-6731	0
298	0	38.468	-40.604	0	161.058
300	10	38.501	-40.334	42	161.196
400	528	39.991	-29.473	2210	167.434
500	1038	41.131	-22.940	4345	172.207
600	1544	42.054	-18.574	6464	176.072
700	2048	42.831	-15.449	8574	179.325
800	2550	43.501	-13.101	10676	182.130
900	3052	44.092	-11.272	12779	184.604
1000	3552	44.619	-9.807	14872	186.810
1100	4051	45.095	-8.606	16961	188.804
1200	4551	45.529	-7.604	19055	190.621
1300	5049	45.928	-6.755	21139	192.291
1400	5548	46.298	-6.027	23227	193.840
1500	6046	46.642	-5.395	25314	195.281
1600	6544	46.963	-4.842	27398	196.625
1700	7042	47.265	-4.353	29484	197.889
1800	7540	47.550	-3.918	31568	199.082
1900	8038	47.819	-3.529	33653	200.209
2000	8536	48.074	-3.178	35739	201.276
2100	9034	48.317	-2.860	37823	202.294
2200	9532	48.549	-2.571	39909	203.265
2300	10029	48.770	-2.307	41989	204.190
2400	10527	48.982	-2.065	44075	205.078
2500	11026	49.185	-1.842	46164	205.928
2600	11524	49.381	-1.636	48248	206.748
2700	12023	49.569	-1.446	50337	207.535
2800	12522	49.751	-1.268	52428	208.297
2900	13022	49.926	-1.103	54521	209.030
3000	13522	50.096	-0.949	56615	209.742
3200	14524	50.419	-0.670	60809	211.094
3400	15529	50.724	-0.423	65016	212.371
3600	16537	51.012	-0.204	69238	213.577
3800	17549	51.285	-0.007	73474	214.720
4000*	18565	51.546	-0.170	77728	215.791
4200	19586	51.795	0.330	82003	216.855
4400	20611	52.033	0.475	86295	217.852
4600	21641	52.262	0.608	90607	218.811
4800	22676	52.482	0.730	94940	219.732
5000	23715	52.695	0.843	99290	220.623

TABLE A.28 Ideal Gas Enthalpy, Absolute Entropy and Equilibrium Constant of Formation for Hydroxyl, OH
 $\Delta H_f^\circ = 9330 \text{ kcal/kmol} = 39034 \text{ kJ/kmol}$

Temperature K	$h_T^\circ - h_{298}^\circ$ kcal/kmol	S° kcal/kmol K	$\log_{10} K_p$	$h_T^\circ - h_{298}^\circ$ kJ/kmol	S° kJ/kmol K
0	-2107	0	-	-8823	0
298	0	43.918	-6.006	0	183.876
300	13	43.962	-5.964	53	184.060
400	724	46.006	-4.264	3031	192.618
500	1430	47.582	-3.244	5987	199.216
600	2134	48.867	-2.565	8934	204.596
700	2841	49.956	-2.082	11895	209.156
800	3553	50.906	-1.720	14875	213.133
900	4272	51.753	-1.541	17887	216.679
1000	5000	52.520	-1.218	20934	219.891
1100	5738	53.223	-1.037	24037	222.834
1200	6487	53.875	-0.887	27161	225.564
1300	7247	54.482	-0.760	30343	228.109
1400	8018	55.055	-0.652	33559	230.504
1500	8800	55.595	-0.559	36844	232.761
1600	9591	56.105	-0.477	40156	234.900
1700	10392	56.590	-0.406	43510	236.931
1800	11202	57.053	-0.343	46901	238.670
1900	12019	57.495	-0.286	50321	240.720
2000	12844	57.918	-0.236	53775	242.491
2100	13676	58.324	-0.190	57259	244.191
2200	14514	58.714	-0.149	60767	245.824
2300	15358	59.089	-0.100	64300	247.394
2400	16206	59.451	-0.077	67858	248.909
2500	17063	59.800	-0.046	71438	250.371
2600	17923	60.137	-0.017	75039	251.782
2700	18788	60.463	0.010	78658	253.146
2800	19655	60.779	0.034	82292	254.470
2900	20528	61.085	0.057	85946	255.751
3000	21404	61.382	0.078	89614	256.994
3200	23166	61.951	0.116	96992	259.376
3400	24940	62.488	0.150	104419	261.624
3600	26726	62.999	0.179	111897	263.764
3800	28522	63.484	0.205	119417	265.795
4000	30327	63.947	0.227	126974	267.733
4200	32140	64.389	0.248	134564	269.584
4400	33962	64.813	0.266	142193	271.259
4600	35790	65.219	0.282	149846	273.059
4800	37626	65.610	0.290	157533	274.696
5000	39467	65.986	0.311	165241	276.270

APPENDIX B

Calculation of Equilibrium Constant and Total Internal Energy

EQUILIBRIUM CONSTANTS

The values of the equilibrium constants given in Table A.17 may be fitted to an equation of the following general form:

$$\log_{10} K = -C_1 + C_2(T-1200) - C_3(T-1200)(T-1600) + C_4(T-1200)(T-1600)(T-2000) - C_5(T-1200)(T-1600)(T-2000)(T-2400) + C_6(T-1200)(T-1600)(T-2000)(T-2400)(T-2800) \quad (\text{B.1})$$

The values of the coefficients C_1 to C_6 are listed in Table B.1.

TABLE B.1 Coefficients C_1 to C_6 for Eq. (B.1)

Equilibrium constant	C_1	$C_2 \times 10^3$	$C_3 \times 10^6$	$C_4 \times 10^9$	$C_5 \times 10^{12}$	$C_6 \times 10^{15}$
K_1	7.742	7.645	3.866	1.607	0.558	0.156
K_2	7.896	6.803	3.366	1.393	0.495	0.151
K_3	8.922	7.910	3.931	1.630	0.586	0.194
K_4	7.531	6.859	3.408	1.418	0.514	0.170
K_5	6.705	6.100	3.014	1.249	0.446	0.141
K_6	3.279	2.463	1.231	0.513	0.184	0.059

TOTAL INTERNAL ENERGY

The molar internal energy of various constituents was calculated by

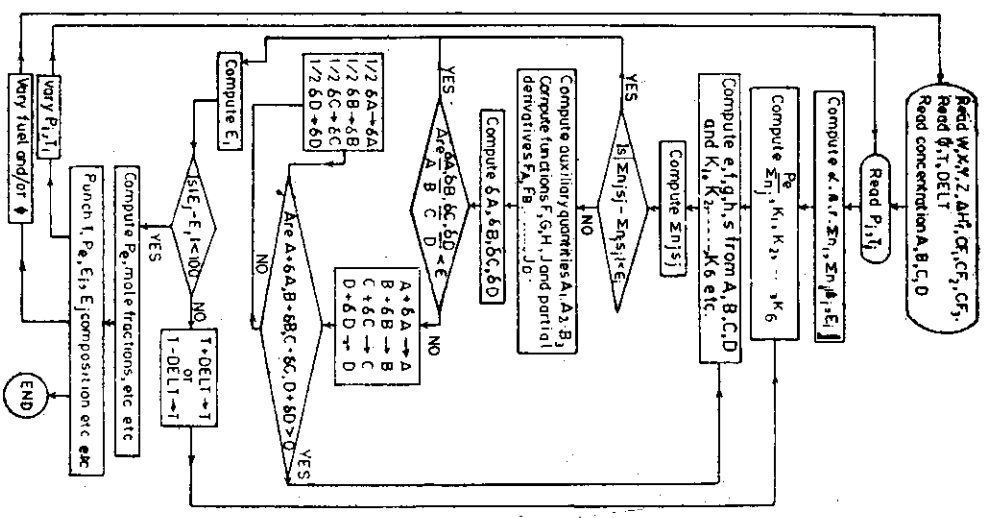
$$e_T = h_T^\circ - RT$$

$$h_T^\circ = \Delta H_f^\circ + \int_{298}^T C_p dT$$

The values of Δh_f° and C_p may be taken from Tables A.16 and A.18.

APPENDIX C

Computer Flow Chart



APPENDIX D

Some Questions and Problems

1 Energy Resources

1. Why is it important to study the energy resources?
2. What are the various types of energy resources? Classify them into exhaustible and inexhaustible resources. Briefly discuss one resource under each category.
3. Write a short report on the available coal, oil and natural gas reserves of India and the world.
4. Discuss the future possibilities for the development of hydraulic and nuclear power.
5. Discuss the various alternative energy resources which are likely to make a significant contribution towards the energy demand in future.

2 Solid Fuels

6. What do you know about the origin of coal? What changes occur in the series from wood to anthracite.
7. What are the different classifications of coal? Briefly describe the basis of each classification.
8. Discuss the following with respect to coal:
 - (i) Proximate and ultimate analysis
 - (ii) Higher and lower calorific value
 - (iii) Coking and non-coking properties
 - (iv) Agglutinating and grindability index.
9. Discuss the differences in the properties of the various types of coal. Why are bituminous and anthracite coals preferred?
10. Write short notes on the following:
 - (i) Coke
 - (ii) Wood charcoal
 - (iii) Fuel briquettes.

3 Liquid Fuels

11. Distinguish between the origin of petroleum and the origin of coal.
12. What are the molecular structures for the following:
Decane, 1-octane, n-heptane, iso-octane (3-ethyl hexane, 2,2,4-trimethyl pentane), diolefin (1,5 heptadiene), benzene, cyclohexane?
13. Briefly discuss the various processes involved during the refining of crude oil.
14. What do you understand by the following processes:
Polymerization, alkylation, and isomerization?
15. List the various tests that are carried out to determine the properties of any petroleum fraction. What is the significance of these tests?
16. Briefly describe the desirable properties of the following fuels:
(i) Motor gasoline,
(ii) aviation gasoline,
(iii) kerosene, and
(iv) diesel.

4 Gaseous Fuels

17. What are the advantages of gaseous fuels over solid and liquid fuels?
18. Compare the important components of the natural and manufactured gases.
19. What do you understand by 'liquefied petroleum gas', 'town gas' and 'bio-gas'?
20. Distinguish between the generation of producer gas and blue-water gas.
21. What are the main properties of fuel gases? Briefly discuss any two.

5 Introduction to the Combustion of Fuels

22. Determine the stoichiometric air/fuel ratio on weight basis for the complete combustion of 1-octene, C_8H_{16} . Also find the air/fuel ratios for mixture strengths of 80 and 120%.
 23. Gaseous propane is burned with 150% theoretical air at 1 atm. If the air is dry, determine the volumetric analysis of the products of combustion and the dew point of the flue gas.
 24. Gaseous propane is allowed to react with 150% theoretical air at a pressure of 1 atm. If the air has an initial relative humidity of 60% at 27°C, determine the dew point temperature of the products of combustion.
25. Ethyl alcohol (C_2H_5OH) is burned with 20% excess air. Determine the dew point temperature of the products of combustion if the total pressure is 1 bar.
 26. Decane ($C_{10}H_{22}$) is burned using an air/fuel ratio of 12:1 by weight. Assuming that all the hydrogen is burned to water vapour, determine the complete volumetric analysis of the flue gas.
 27. Determine the excess (or deficiency) of air in a furnace when the water saturated flue gases are found to contain the following (on volume basis):
 CO_2 : 21%, CO : 2.5%, O_2 : 5.5%, N_2 : 71%.
 28. Fuel contains 86% C and 14% H_2 by weight.
A fuel gas is composed of 20% CH_4 , 40% C_2H_6 , 40% C_3H_8 on a volume basis. The percentage volumetric analysis of the dry products of combustion of this fuel is:
 CO_2 : 10.5, O_2 : 3; CO : 1; N_2 : 86.5
- Determine:
- (a) The gravimetric analysis of fuel,
 - (b) the theoretical air/fuel ratio, and
 - (c) the percentage of excess air.
29. A fuel has the following percent analysis by weight:
C: 86; H_2 : 6; S: 3; O_2 : 2.5; ash: 2.5.
For an air/fuel ratio of 12:1, calculate
(a) The mixture strength as a percentage rich or lean
(b) The volumetric analysis of the dry products of combustion.
Air contains 23% O_2 by weight.
 30. A fuel has an ultimate percent analysis of 86 C and 5.4 H, the remainder being incombustible. A partial volumetric analysis of the dry products of combustion shows 13% CO_2 and 3.5% O_2 and it is suspected some CO is present. Estimate:
(a) The complete volumetric analysis of the dry exhaust gases, and
(b) the air/fuel ratio by weight based on the fuel as fired.
Air contains 21% O_2 by volume and all the H and C have been burned.
 31. The flue gas analysis by volume in a boiler trial was
 CO_2 : 11%, CO : 1.0%, O_2 : 8.0%, N_2 : 80%
and the coal analysis as burned was
C: 80%, H_2 : 4.5%, O_2 : 5.5%, incombustible: 10%.
- Calculate:
- (a) The weight of air supplied per kg of coal, and
 - (b) the percentage excess air.

32. A fuel oil has the following gravimetric analysis:

C: 84%, H₂: 14%, O₂: 1%, S: 1%

It is burned with 50% excess air. Determine:

- (a) The weight of air supplied per kg of fuel, and
 (b) the volumetric analysis of the wet products of combustion.
 33. The volumetric analysis of a natural gas is 16% C₂H₆ and 84% CH₄. Determine:
 (a) The stoichiometric air/fuel ratio,
 (b) the percentage by weight of the carbon and hydrogen in the fuel, and
 (c) the weight of CO₂ and H₂O formed per kg of fuel.

6 Fundamentals of Chemical Kinetics

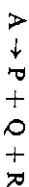
34. Why is the study of chemical kinetics important?
 35. Explain, giving examples where necessary, the following:
 (i) Reaction rate
 (ii) Reaction order
 (iii) Half life of a reaction
 (iv) Complex reactions.
 36. Derive expressions for the half life of the following reactions:
 (i) Zero order reaction
 (ii) First order reaction
 (iii) Bimolecular reaction for the case of equimolecular initial concentrations.
 37. For the process $A \rightleftharpoons M$
 let a_0 and m_0 represent the initial concentrations of the two chemical species involved. Show that when x molecules of products have been formed (and correspondingly x molecules of reactants have disappeared)

$$\frac{k_1}{k_1 + k_2} \log_e \frac{x'}{x' - x}$$

$$\text{where } x' = \frac{ka_0 - km_0}{k + k}$$

38. Consider that for some chemical reactions, the initial concentration of all reactants is equal to a_0 . Let x represent the change of a_0 in time t . Derive expressions for the reaction rate constant k in terms of a_0 , x , and t for first, second and third order reactions.
 39. What do you understand by the following:
 (i) Reversible reactions of the first and second order
 (ii) Parallel reactions of the first, second and mixed order
 (iii) Consecutive reactions of the first order.

40. Calculate the percentage decomposition of butane during 6 s at 650°C ($k = 0.06 \text{ s}^{-1}$) in a thermal cracking unit. Derive any formula used.
 41. What do you understand by the terms 'unbranching chain' and 'chain branching' reactions. Give the schematic representations for the above reactions.
 42. What are the steps involved in the mechanism of a chain reaction. Briefly discuss the kinetics of chain reactions.
 43. Discuss the law of Arrhenius for the effect of temperature on the reaction rate constant. Show how the value of E can be determined experimentally.
 44. In a decomposition reaction:

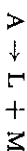


the partial pressure of the reactant $A(p)$ is used as the measure of its concentration as given in the following table:

t (min)	0	7	11	16	20	23	27
p (mm)	230	184	164	140	124	112	99

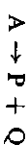
Determine the order of the reaction and the reaction rate constant.

45. For a decomposition reaction:



the time required for 25% decomposition of the reactant A is 130 s at 530°C and 80 s at 540°C. Calculate:

- (i) k_{530} and k_{540} for the reaction, and
 (ii) activation energy E for the reaction.
 46. Explain what do you understand by the 'activation energy' of a reaction.
 47. In a decomposition reaction represented as



the reaction rate constant k is found to have the following values:

Temperature °C	$k \times 10^4$
540	1.6
550	2.8
560	4.5
580	12.1

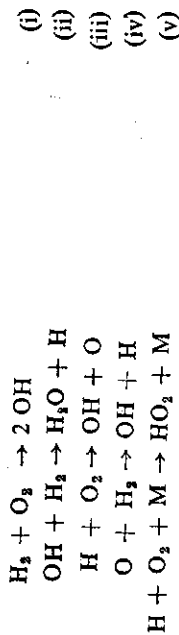
Determine:

- (i) The activation energy of reaction E and compare the result with the value determined graphically.
 (ii) The time for 25% of the reactant to be decomposed at 580°C.
 48. Distinguish between the 'collision theory' and the 'activated complex theory' of the reaction rates.

49. Briefly discuss the concept of potential energy surface.

7 Kinetics of Chemical Chain Reactions

50. Give a complete reaction scheme of the hydrogen-bromine reaction.
51. Discuss all the important reactions which occur during the initiation, propagation, and termination phases of the chain reaction of hydrogen with oxygen.
52. Discuss the three explosion limits of hydrogen and oxygen combustion.
53. Discuss the mechanism of hydrogen-oxygen reaction.
54. Consider the following simplified system of reactions involving hydrogen and oxygen between the second and third explosion limits:



Write down the differential equations for the variation in concentration of the principal chain carriers in the system. If the steady-state condition is applied to the equations, show that the overall rate of the reaction will increase with increasing pressure of the reactants.

55. Give a reaction scheme for $\text{CO} + \text{O}_2$ combustion (both for dry $\text{CO} + \text{O}_2$ and the water catalyzed reaction between CO and O_2). Discuss the significance of the second explosion limit for the $\text{CO} + \text{O}_2$ reaction.
56. Explain the phenomenon of cool flames. Describe a simple experiment to detect the cool flames and determine their duration.
57. Distinguish between cool flames and second stage ignition.
58. Discuss the main kinetic features of hydrocarbon oxidation by Semenov's hypothesis of 'degenerate branching'. Illustrate your answer with a suitable example.
- ### 8 Thermodynamics of Combustion
59. Derive an expression for the change in the internal energy of a chemical reaction occurring at constant volume.
60. Derive an expression for the change in the enthalpy of a chemical reaction occurring at constant pressure.
61. Distinguish between the enthalpy of combustion and the internal energy of reaction. How are they related?

62. Establish a relation between the change in the enthalpy of reaction and the temperature.

63. Show that the relationship between the enthalpy of combustion (ΔH_R) and the molal enthalpy of fuel (h_f) is given by

$$\Delta H_R = \left(m h_{\text{CO}_2} + \frac{n}{2} H_{2\text{O}} \right) - \left[h_f + \left(m + \frac{n}{4} \right) h_{\text{O}_2} \right]$$

where m and n are the number of carbon and hydrogen atoms present in the fuel.

64. Why is the reference standard state of 25°C required? Show that the molal enthalpy of fuel h_f at any temperature T may be written as:

$$h_{f,T} = h_{f,298} + \int_{298}^T C_p \cdot dT$$

where $C_p = a + bT + cT^2 + dT^3$.

65. Explain the terms 'standard enthalpy of formation' of a compound (ΔH_f°) and the 'standard bond dissociation energy' for the bond A—B (DH°).

66. Define the term 'adiabatic flame temperature'. Why is it important in combustion studies? How it can be determined for a combustion reaction?

67. Making use of the Gibb's function for a mixture of ideal gases, derive the Van't Hoff's equation

$$\frac{d(\log_e K_p)}{dT} = \frac{(\Delta H_R)_T}{RT^2}$$

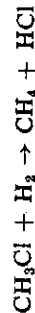
where K_p is the equilibrium constant and $(\Delta H_R)_T$ the enthalpy of combustion at absolute temperature T .

68. What do you understand by the 'equilibrium constant'? Discuss the variation of equilibrium constant with temperature. Show that the logarithm of the specific rate of a reaction is a linear function of the reciprocal of the absolute temperature.

69. Lay down the method for calculating the equilibrium flame temperature for the combustion of CH_4 with stoichiometric amount of air. The combustion is to take place at constant pressure under adiabatic conditions. Write down the necessary equations to determine the equilibrium composition and final temperature. Consider all the important reactions involved.

70. Same as question 69 except that the combustion takes place at constant volume under adiabatic conditions.

71. In a flow calorimeter experiment for exothermic reaction:



ΔH_r was found to be -82.30 kJ/mole at 225°C . Determine the value of the standard enthalpy of reaction $\Delta H_{r,298}$ values of C_p at 400 K are given as:

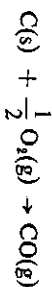
$$\text{C}_p: \text{CH}_4(\text{g}) = 41.28 \text{ J/mole K}$$

$$\text{HCl}(\text{g}) = 29.11 \text{ J/mole K}$$

$$\text{CH}_3\text{Cl}(\text{g}) = 48.46 \text{ J/mole K}$$

$$\text{H}_2(\text{g}) = 28.56 \text{ J/mole K}$$

72. Calculate the enthalpy of reaction for the reaction:



73. Calculate the enthalpy of reaction for the reaction:



74. Calculate the enthalpy of formation of propane C_3H_8 .

75. Determine the enthalpy of combustion and internal energy of reaction for C_2H_2 .

76. Determine the enthalpy of combustion ΔH_r and internal energy of reaction ΔU_r for propane gas burning with 80% theoretical air.

77. Determine ΔH_r° for the reaction



Given that ΔH_r° for the reaction $\text{CO} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2$ is -67.637 kcal/gmol and $\Delta H_{f,298}^\circ$ for CO_2 is -94.054 kcal/gmol.

78. Determine the internal energy of reaction, ΔU_r for propane at 600 K.

79. Determine the equilibrium composition of a system where:

$$\frac{\text{C}}{\text{O}} = 0.333; \quad \frac{\text{H}}{\text{O}} = 0.0; \quad \frac{\text{N}}{\text{O}} = 0.0$$

at 3000K and 10 atm pressure.

80. Calculate the enthalpy of combustion of hydrogen gas at 2600 K for the gas phase reaction.

81. Determine the enthalpy of formation (ΔH_f°) of propane $\text{C}_3\text{H}_8(\text{g})$, given the following data:

Enthalpy of combustion (ΔH_c°) of $\text{C}_3\text{H}_8(\text{g}) = -2221493$ kJ/kmol

Enthalpy of formation (ΔH_f°) of $\text{CO}_2(\text{g}) = -393769$ kJ/kmol

Enthalpy of formation (ΔH_f°) of $\text{H}_2\text{O}(\text{l}) = -286028$ kJ/kmol

82. Compute the enthalpy of reaction at 25°C for the following reaction:



Given that at 25°C the enthalpy of formation are:

$$h_{f,298}^\circ(\text{CO}_2) = 93.990 \text{ kcal/kgmol}$$

$$h_{f,298}^\circ(\text{CO}_2) = -26.399 \text{ kcal/kg mol}$$

$$h_{f,298}^\circ(\text{H}_2\text{O}) = -68.273 \text{ kcal/kg mol}$$

83. The lower heating value (LHV) at constant pressure for methane at 25°C is 191.759 kcal/kmol. Calculate

(i) Higher heating value (HHV) at constant pressure,

(ii) HHV at constant volume,

(iii) LHV at constant volume, and

(iv) HHV at constant pressure at 600K .

84. Calculate the C-C bond energy for ethane if its heat of formation is -20.5 kcal/mol and the heat required for the dissociation of carbon and hydrogen are $+173$ and $+105$ kcal/mol respectively. The bond energy of C-H bond is 98 kcal per mol.

85. One mole of CO_2 is mixed with one mole of H_2 . Determine the equilibrium composition for the reaction $\text{CO}_2 + \text{H}_2 \rightleftharpoons \text{CO} + \text{H}_2\text{O}$, if the temperature is (i) 1000K , and (ii) 2000K .

86. Determine the equilibrium composition for a system where $\text{C}/\text{O} = 0.25$, $\text{H}/\text{O} = 1.00$, $\text{N}/\text{O} = 0.00$ at 2600K and 1 atm pressure. Consider the dissociation of CO_2 , H_2O , and O_2 .

87. Determine the equilibrium composition for the constant pressure combustion of $\text{CO} + (1/2) \text{O}_2$ at 3000K and 10 atm pressure.

88. Carbon monoxide (CO) and oxygen (O_2) in equimolar proportions are allowed to attain equilibrium at 1 atm. pressure. Determine the equilibrium constant (K_p) for the reaction if the relative concentrations of CO and CO_2 are $2:3$ in the high temperature products.

89. $2 \text{ m}^3/\text{s}$ of C_2H_6 at 1.5 atm pressure and 300K are supplied along with 120% stoichiometric air (preheated to 400K) to a furnace. Heat is transferred from the products of combustion to generate steam. The products leave the boiler at 500K . Determine the rate of heat transfer to the steam. Assume that combustion is complete and there is no dissociation of the products.

90. Liquid octane ($n\text{-C}_8\text{H}_{18}$) and air in 50% excess, enters a combustion chamber in steady flow at 1 atm and 25°C . Determine the amount of heat which must be removed per mole in order to cool the combustion products to 800K . The enthalpy of vaporization of fuel may be taken as 9910 kcal/kmol.

91. The equilibrium constant for the reaction of hydrogen and oxygen to steam is 3 at about 4000K . When steam is heated to this temperature, what fraction is dissociated into H_2 and O_2 at 1 atm total pressure? Assume that no other type of dissociation occurs.

92. (a) Determine the flame temperature at the end of constant pressure adiabatic combustion of CO with stoichiometric air (i) with, and (ii) without dissociation of CO_2 . The initial pressure and temperature may be taken as 1 atm and 27°C respectively. (b) Same as (a) except that combustion takes place at constant volume under adiabatic conditions.

93. Determine the heat rejected when a mixture of methane with 20% excess air, initially at 25°C temperature and 1 atm pressure, is completely burned and the final temperature is determined to be uniform at 600K in the following cases:

- (i) When the process occurs in a rigid container, and
 (ii) when the process is steady flow at constant pressure.

94. A combustible bomb is filled with hydrazine vapour at 1 atm pressure at its normal boiling point. The hydrazine is then exploded, decomposition takes place, and a steady high pressure is reached after the reaction products have reached equilibrium. Assuming no heat loss from the gas phase, give a method for calculating the end pressure. State clearly the end products you expect, the minor components that you believe you can ignore, and why. What principal gases would the bomb contain after it cooled to room temperature?

95. Determine the temperature of the products of combustion of hydrogen and 100% excess air if the reactants are at 300K and the combustion process takes place adiabatically (i) at constant pressure, and (ii) at constant volume.

96. Given the following relation between the value of K_p at two different temperatures:

$$\log_e \frac{K_{p2}}{K_{p1}} = - \frac{\Delta H_R^\circ}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right)$$

where ΔH_R° is the average standard state enthalpy of reaction for the given temperature limits. Discuss the importance of this equation for exothermic and endothermic reactions.

97. Compute the value of K_p for the dissociation reaction



when 10% CO_2 is dissociated at 2 atm. Determine the temperature for the above reaction.

98. The following table gives the experimental data for the reaction:

$$\text{SO}_2 \rightleftharpoons \text{SO} + \frac{1}{2} \text{O}_2$$

$T(\text{K})$	K_p
900	0.146
1000	0.518
1100	1.45

Calculate the value of ΔH_R for the above reaction at 1000K in kcal/kmol using the integrated form of the Van't Hoff's equation.

99. Determine the maximum flame temperature when methane gas is burned with stoichiometric amount of air at constant pressure of 1 atm, both reactants entering at 25°C. Assume that the combust-

ion with respect to carbon is only 80% complete, i.e. 20% of the carbon in methane is burned only to CO. The dissociation of the products at high temperatures may be neglected.

100. CO_2 is heated to 3000K. CO_2 decomposes into CO and O_2 by the reaction, $\text{CO}_2 \rightleftharpoons \text{CO} + \frac{1}{2} \text{O}_2$. If $K_p = 2.93$ for the reaction, $\text{CO} + \frac{1}{2} \text{O}_2 \rightleftharpoons \text{CO}_2$ and the total pressure is 4 atm, assuming only CO, O_2 and CO_2 are present in the equilibrium mixture, calculate the equilibrium composition.

101. Determine the adiabatic flame temperature and explosion pressure for the constant volume combustion of CO with 50% excess air. The initial conditions are 1 atm and 27°C. Assume that no dissociation of the products takes place.

102. Describe a method of calculating the equilibrium flame temperature and mixture composition following the constant pressure combustion of propane (C_3H_8) with stoichiometric amount of air. State clearly any assumptions made.

103. Determine the equilibrium composition (mole fractions) of the products of combustion at 2400K for the system in which: C/O = 0.25, H/O = 1.0, and N/O = 3.76. The combustion is to take place at constant pressure of 1 atm under adiabatic conditions. In order to simplify the problem consider only the equilibrium of important reactions involved.

104. Find the temperature at which H_2O becomes 5% dissociated into H_2 and O_2 at a pressure of 5 atm.

9 Laminar Flame Propagation

105. Why is the study of laminar flame propagation important?

106. What do you understand by the structure of a premixed flame? Discuss the nature of concentration and temperature profiles in the preheat and reaction zones of a flame.

107. Discuss the factors which govern the shape of a bunsen flame. Draw the curves of burning velocity and flow pattern across a burner tube.

108. Discuss the flame shape for a laminar combustion wave in a tube with one end closed.

109. What are the different theories explaining the phenomenon of laminar flame propagation.

110. Formulate mathematically the problem of one dimensional laminar flame propagation in premixed combustible mixtures. Set up the differential equations of thermal conduction and diffusion during forced flow and deduce the relationship between the temperature and concentration profiles across a plane combustion wave. State clearly any assumptions made.

111. Enumerate the various assumptions made in the derivation of the

Semenov equation for the determination of burning velocity of a combustible mixture.

10 Determination of Burning Velocities

112. What is the importance of laminar burning velocity in flame research? How is it defined?
113. What are the different methods of observing a flame front? Illustrate the relative positions of the reaction zones of a conical flame as observed by the direct, Schlieren and shadow photographic techniques.
114. What are the various methods of measuring burning velocity? Briefly discuss their relative merits and demerits.
115. Briefly describe any one experimental technique of measuring laminar burning velocity of a premixed gaseous combustible mixture.
116. How can the burning velocity be determined at any instant during the process from a pressure-time record in the case of a spherical rigid vessel with central ignition and isotropic propagation.
117. Describe the soap-bubble technique of measuring the laminar burning velocity of a combustible mixture.
118. Show with the help of suitable diagrams how the flame front surface area and the burning velocity can be determined by the use of the cylindrical burner method.
119. Discuss the influence of the following factors on the laminar burning velocity of a gaseous combustible mixture:
 - (i) Mixture composition
 - (ii) initial pressure,
 - (iii) initial temperature, and
 - (iv) additives.
120. How is it possible to compare the values of burning velocity obtained by different methods? Refer Table 10.1, for obtaining the agreeable values of burning velocity by applying the correction factors.
121. Explain what you understand by the term 'normalized burning velocity'.

11 Turbulent Flame Propagation

122. Distinguish between laminar and turbulent flames. Draw neat sketches to illustrate them.
What are the different fields of application of the turbulent flames?
123. Describe with the help of a suitable sketch a turbulent flame model showing the boundaries of flame brush and the mean surface.

124. Define the term 'turbulent burning velocity'. How can the turbulent burning velocity be measured experimentally?
125. What are the reasons for the increased rate of burning of a fuel-air mixture in a turbulent flame as compared with a laminar flame?
126. Discuss the effect of turbulence on combustion wave propagation.
127. Briefly discuss the concept of turbulent flow.
128. Discuss the influence of the following factors on the turbulent burning velocity:
 - (a) Fuel type,
 - (b) initial temperature,
 - (c) pressure, and
 - (d) air/fuel ratio.
129. What do you understand by the structure of a turbulent flame? Illustrate your answer with a neat sketch.
130. Deduce the expression for turbulent burning velocity in case of (i) small scale turbulence and (ii) large scale turbulence.
131. What are the different theories explaining the phenomenon of turbulent flame propagation?

12 Flame Stabilization

132. Why is the study of flame stabilization important?
133. Draw the characteristic stability diagram for the open burner flames and discuss the limits of flashback, blow-off or blow-out.
134. Describe the principles of stabilization of combustion waves in gas streams. Illustrate your answer with neat diagrams of the burning velocity and the critical boundary velocity gradient near the burner wall.
135. Describe the different methods of flame stabilization in gas streams.
136. What do you understand by the flame stretch? Discuss the effect of flame stretch on the burning velocity. Derive an expression for the 'flame stretch factor' (or Karlovitz number, K) in case of flame propagation in a velocity gradient.
137. Define the terms: quenching distance, penetration distance and dead space. Illustrate the difference between the penetration distance and the dead space near a vertical wall and above the burner rim.

13 Diffusion Flames

138. Distinguish between the premixed and diffusion flames.
139. What do you understand by the 'over-ventilated' and 'under-ventilated' diffusion flames? Discuss the various flame shapes and zones that can be obtained on a burner. Illustrate your answer with neat sketches.
140. With the help of a suitable diagram discuss the progressive change

that takes place from laminar diffusion to turbulent diffusion flame with the increase in nozzle flow velocity.

141. Describe the structure of a laminar diffusion flame. Draw the concentration profiles (qualitative only) at different heights above the burner port for a hydrogen diffusion flame.
142. Consider two cylindrical diffusion flame burners of different diameters. Show that:
- The diffusion flame height is proportional to the fuel flow rate for laminar flow.
 - The diffusion flame height is independent of the fuel flow rate for turbulent flow.
143. Mathematically formulate the problem of a cylindrical diffusion flame. Write down the solution of the equation specifying clearly the boundary conditions of the problem.
144. Discuss the theory of turbulent diffusion flame.

14 Detonation Waves in Gases

145. Distinguish between a shock wave and detonation wave.
146. Consider that a shock wave is travelling in a medium of combustible mixture and that in the wave front chemical reaction occurs and goes to completion. Write down the necessary equations for the unburned and the burned gas regions and show that the detonation velocity equals the sum of burned gas velocity and sound velocity in the burned gas. Discuss the significance of the Chapman-Jouguet point for detonation.
147. Briefly discuss the steady-state propagation of detonation waves in gases.
148. Lay down the method for calculating the detonation velocity for a given combustible mixture and initial conditions.
149. A steady state explosion wave is travelling in a hydrocarbon-air mixture for which the constant pressure heat of reaction is 666 kcal/kg of mixture. The inflammable mixture is at rest and at a temperature of 16°C and a pressure of 1 atmosphere. For the two limiting cases in which:
- The wave speed is the maximum for slow combustion, and
 - the wave speed is the minimum for detonation.
- Determine the speed of the wave front and the burned gas.
150. Explain clearly what do you understand by the terms 'detonation' and 'deflagration'. How are detonation waves initiated in combustible mixtures?

15 Ignition

151. How does the ignition of a combustible mixture take place?
152. Distinguish between 'self-ignition' and 'forced-ignition'.

153. Using the equations for the rate of heat generation and heat lost in a vessel, explain the conditions under which an explosion can occur. Define clearly the 'self-ignition temperature' of the mixture.

154. Deduce the Semenov's equation

$$\log_e \frac{P_{ign}}{T_0} = \frac{E}{2RT_0} + \text{const}$$

for the limit relation between the ignition pressure and vessel wall temperature for the self-ignition of gaseous mixtures.

155. Explain the process of self-ignition. What conditions determine the temperature of self-ignition?
156. What do you understand by the 'induction period'?
157. What do you understand by the 'ignition limits'?
158. Briefly discuss the ignition of a reaction mixture by (i) pilot flames, (ii) hot gases, (iii) shock waves.
159. Explain the phenomenon of spark ignition.
160. What are the effects of the following factors on the minimum ignition energy: (i) electrode type, (ii) pressure, (iii) temperature, (iv) diluents, (v) turbulence.

16 Combustion of Liquid and Solid Fuels

161. Discuss some of the combustion characteristics of liquid and solid fuels.
162. What are the different types of experimental techniques developed for the study of the combustion of fuel droplets?
163. Discuss the steady-state theory for the burning of a single spherical droplet surrounded by a spherical symmetrical flame front. State clearly any assumptions made.
164. What are the effects of oxygen concentration, pressure and flame radius on the mass burning rate of a fuel droplet with and without natural convection?
165. Discuss the shape of the flame surface surrounding a single fuel droplet during burning with natural convection.
166. Briefly describe the mode of combustion of fuel droplets in sprays.
167. State what happens to a piece of coal when heated gradually in a furnace in the presence of air.
168. Discuss the oxidation mechanism of carbon in the coal. Which theory of oxidation is considered more acceptable?
169. Briefly discuss the kinetics of the heterogeneous combustion of carbon.
170. Explain clearly the meaning of the term 'transfer number' of a liquid fuel.
171. Derive the expressions for the transfer number and the burning

time of liquid fuel droplet burning in an atmosphere of air. State clearly any assumptions made.

172. Estimate the transfer number and the life time of a liquid hydrocarbon (C_nH_{2n}) fuel droplet burning in still air from the following data:

Initial droplet diameter (d_0) = 0.005 cm

Heat of combustion of fuel (H) = 10,500 cal/g

Density of droplet (ρ_l) = 0.8 g/cm³

Latent heat of vaporization of fuel (L) = 83 cal/g

Exchange coefficient = $\gamma = D_p \rho_g = 0.5 \times 10^{-3} \frac{g}{cm \cdot s}$

Specific heat of gases at constant pressure (C_p) = 0.3 cal/g, °C

Boiling point of fuel (T_b) = 90°C

Temperature of surrounding air (T_g) = 20°C.

Assume that the heat that must leave the gas to vaporize a unit mass of fuel is $Q = L + 0.479 T_g$ cal/g.

173. Pure ethyl alcohol C_2H_5OH burns from a wick dipping into a reservoir of liquid at 20°C. The surrounding air is also at 20°C. Assuming that the temperature taken up by the surface of the wick equals the boiling point of the liquid, determine the transfer number of fuel, given the following data:
For C_2H_5OH , stoichiometric ratio $r = 2.09$ g O_2 /g fuel

heat of combustion of fuel $H = 6710$ cal/g

latent heat of vaporization $L = 204$ cal/g

174. Show that it is possible to form a link between liquid and solid fuels on the basis of transfer numbers and that the solid fuels form the extreme member of the liquid fuel family.

17 Combustion Applications

175. List some of the areas which are finding successful application of the scientific principles of combustion.
176. Discuss the over feed principle of firing coal with the help of a diagrammatic sketch.
177. Describe the different methods of firing coal. Briefly discuss the working and construction of the over feed and under feed stokers.
178. Discuss the fields of application of the pulverized fuel firing. Describe the working of the pulverized coal burners and the cyclone furnace. Indicate the future trends.
179. List some of the oil burners in use for domestic and industrial heating.
180. Discuss the fields of application of oil burners. How are they classified? Briefly describe their working principles.

181. What are the different types of gas burners? Where are they used? Briefly describe their working principles.

182. Briefly discuss the combustion process in spark ignition engines.

183. Briefly discuss the combustion process in compression ignition engines.

184. What are the different types of combustors used in gas turbines and jet engines? Discuss some of the problems relating to the operation of the combustors.

185. Enumerate some of the desirable characteristics of propellants for rocket engines. Briefly discuss the types of liquid and solid propellants.

18 Air Pollution

186. Why is the study of air pollution important?

187. What are the types of air pollution? Briefly discuss the harmful effects of air pollution on human health. With the help of Table 18.1 compare the threshold limit values of various pollutants.

188. What do you understand by air pollution from the combustion of fossil fuels?

189. What are the major sources for the formation of the following pollutants:

Grit and dust, smoke, sulphur dioxide, carbon monoxide? Briefly discuss some of the control measures.

190. What do you understand by air pollution from automobiles? Briefly discuss the major sources for automobile emissions and their means of control.

191. List the various means to control the hydrocarbon, carbon monoxide and nitric oxide concentration in the exhaust from an automobile. What are the effects of control means on the exhaust pollutants?

192. Briefly describe some of the advanced control systems which are adopted or are under investigation for reduction in the pollutant concentrations.

193. Compare the emission by diesel engines and the emission by gasoline engines.

194. What do you understand by exhaust emission standards?

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