UNIVERSITI SAINS MALAYSIA

Second Semester Examination
2015/2016 Academic Session

June 2016

ESA 368/3 High Speed Aerodynamic
[Aerodinamik Berkelajuan Tinggi]

Duration : 2 hours
[Masa : 2 jam]

Please ensure that this paper contains **FIFTEEN (15)** printed pages and **THREE (3)** questions before you begin examination.

*[Sila pastikan bahawa kertas soalan ini mengandungi **LIMA BELAS (15)** mukasurat bercetak dan **TIGA (3)** soalan sebelum anda memulakan peperiksaan].*

Instructions : Answer all **THREE (3)** questions.

[Arahan : *Jawab kesemua **TIGA (3)** soalan].*

Answer all questions in English only.

[Jawab semua soalan di dalam Bahasa Inggeris sahaja].

Each question must begin from a new page.

[Setiap soalan mestilah dimulakan pada mukasurat yang baru].

Flow tables and charts are attached at the end of the question paper.

[Jadual dan carta aliran dikepilkan di belakang kertas soalan ini].

[Setiap soalan mestilah dimulakan pada mukasurat yang baru].

In the event of any discrepancies, the English version shall be used.

[Sekiranya terdapat sebarang percanggahan pada soalan peperiksaan, versi Bahasa Inggeris hendaklah diguna pakai].

For the questions that require explanation, you are expected to answer the questions as detailed as possible with properly and fully constructed sentences to receive full credits.

[Bagi soalan-soalan yang memerlukan penerangan, anda di minta untuk menjawab soalan-soalan tersebut secara terperinci dengan menggunakan ayat yang disusun lengkap untuk menerima kredit yang penuh].

Each student is allowed to bring an A4-sized sheet of self-prepared two-page summary note.

[Setiap pelajar dibenarkan untuk membawa sehelai nota ringkasan bersaiz A4 yang mempunyai dua mukasurat yang ditulis sendiri].

Partial credits will be given accordingly to the work shown correctly.

[Sebahagian kredit akan diberikan secara berpatutan untuk jalan kerja yang ditunjukkan dengan betul].

For standard air, use R = 287 J/kg.K and gamma = 1.4.

[Untuk udara biasa gunakan R = 287 J/kg.K dan gamma = 1.4].

Answer **THREE (3)** questions.

1. Using a simple case of a blunt-nose reentry capsule moving at a supersonic speed,

[a] Describe what a shock wave is, list its types, and illustrate one example for each type.

(8 marks)

[b] Explain why a shock wave is formed, based on the argument using the speed of sound, as discussed in class.

(10 marks)

[c] Discuss the behavior of the flow downstream of the curved shock wave, e.g., how the properties of the air changes in the region after the shock.

(12 marks)

Support all your answers above with a schematic drawing of the problem, and other graphics and/or formulas as needed.

2. Air flows over a plane surface at a Mach number of 3.5 with the pressure in the flow being 100 kPa. The surface turns through an angle leading to the generation of an oblique shock wave whose strength is such that the pressure downstream of the shock is 548 kPa. Find the turning angle that causes the shock wave.

[a] Describe what the problem is, with relevant drawings, and explain the strategy to solve it.

(15 marks)

[b] Solve the problem. Use equations to solve this problem (not using Flow Tables), and show your calculations.

(5 marks)

3. Air at a pressure of 350 kPa, a temperature of 80 degree Celsius, and a velocity of 180 m/s enters a convergent-divergent nozzle. A stationary normal shock occurs in the nozzle at a location where the Mach number is 2. If the air mass flow rate through the nozzle is 0.7 kg/s and if the pressure on the nozzle exit plane is 260 kPa, find the nozzle areas (i) at the throat, (ii) at the shock location, and (iii) at the exit. Find also the temperature and pressure at the nozzle exit. Finally, find the changes in the entropy through the nozzle (labeled with its proper unit).

Solve the problems above by using the 3-Step Approach:

[a] Demonstrate your understanding by drawing the schematic of the problem (complete with proper labeling), describing the flow behavior throughout the nozzle, and stating clearly what the question needs.

(15 marks)

[b] Strategize by outlining in detail the approaches and steps used, including the equations involved, to solve the problems.

(20 marks)

[c] Solve the problems by calculating the numerical values of the required parameters. Show your calculations. You can use the Flow Tables to solve this problem.

(15 marks)

Jawab ***TIGA (3)*** *soalan.*

1. *Dengan menggunakan kes mudah iaitu sebuah kapsul masuk-atmosfera bermuncung bulat yang sedang bergerak dengan kelajuan supersonik,*

   [a] *Di dalam satu perenggan, jelaskan apakah itu gelombang kejut, nyatakan jenis-jenisnya, dan berikan satu contoh bagi setiap jenis.*

   (8 markah)

   [b] *Terangkan mengapa sesuatu gelombang kejut dihasilkan, berdasarkan hujah menggunakan halaju bunyi, seperti yang dibincangkan di dalam kelas.*

   (10 markah)

   [c] *Bincangkan tingkah laku aliran itu di hilir gelombang kejut bengkok, contohnya, bagaimana sifat udara itu berubah di dalam kawasan selepas kejutan itu.*

   (12 markah)

Sokong jawapan anda di atas dengan gambarajah skema bagi soalan itu, dan gambarajah-gambarajah dan/atau persamaan-persamaan yang diperlukan.

2. *Udara mengalir di atas sebuah permukaan dengan halaju Mach 3.5, dengan tekanan udara 100 kPa. Permukaan itu membengkok dengan satu sudut yang menghasilkan gelombang kejutan serong dengan kekuatan yang meningkatkan tekanan udara kepada 548 kPa selepas kejutan tersebut. Carikan sudut belok yang mengakibatkan gelombang kejut ini.*

   [a] *Jelaskan masalah ini, dengan lakaran yang bersesuaian, dan jelaskan strategi untuk menyelesaikannya.*

   (15 markah)

   [b] *Selesaikan masalah ini. Gunakan persamaan untuk menyelesaikannya (bukan menggunakan Jadual Aliran), dan tunjukkan jalan kerja anda.*

   (5 markah)

3. *Udara dengan tekanan 350 kPa, suhu 80 darjah Celcius, dan halaju 180 m/s memasuki sebuah corong menirus-mencapah. Sebuah gelombang kejutan tegak kaku berada di dalam corong itu di lokasi di mana halaju Machnya adalah 2. Jika kadar aliran jisim melalui corong itu adalah 0.7 kg/s dan jika tekanan udara di pintu keluar corong adalah 260 kPa, kirakan luas corong (i) di leher, (ii) di lokasi gelombang kejut, dan (iii) di pintu keluar. Kirakan juga suhu di pintu keluar corong itu. Akhir sekali, tentukan perubahan entropi di sepanjang corong (dilabel secara tepat dengan unitnya sekali).*

Selesaikan masalah di atas dengan menggunakan Pendekatan 3-Langkah:

[a] Tunjukkan pemahaman anda dengan melakarkan gambarajah skema masalah itu (lengkap dengan label yang sesuai), menerangkan aliran udara di sepanjang corong itu, dan menyatakan dengan jelas apa yang diminta oleh soalan itu.

(15 markah)

[b] Nyatakan strategi dengan menggariskan pendekatan dan langkah yang diambil, termasuk persamaan yang digunakan untuk menyelesaikan masalah ini.

(20 markah)

[c] Selesaikan masalah ini dengan mengira nilai parameter yang diminta. Tunjukkan jalan kerja anda. Anda boleh menggunakan Jadual Aliran untuk menyelesaikan masalah ini.

(15 markah)

APPENDIX/*LAMPIRAN*

APPENDIX B

Isentropic Flow Tables for $\gamma = 1.4$

M	T_0/T	p_0/p	ρ_0/ρ	a_0/a	A/A^*	θ
0.00	1.000 00	1.000 00	1.000 00	1.000 00	—	—
0.02	1.000 08	1.000 28	1.000 20	1.000 04	28.942 13	—
0.04	1.000 32	1.001 12	1.000 80	1.000 16	14.481 48	—
0.06	1.000 72	1.002 52	1.001 80	1.000 36	9.665 91	—
0.08	1.001 28	1.004 49	1.003 20	1.000 64	7.261 61	—
0.10	1.002 00	1.007 02	1.005 01	1.001 00	5.821 83	—
0.12	1.002 88	1.010 12	1.007 22	1.001 44	4.864 32	—
0.14	1.003 92	1.013 79	1.009 83	1.001 96	4.182 40	—
0.16	1.005 12	1.018 04	1.012 85	1.002 56	3.672 74	—
0.18	1.006 48	1.022 86	1.016 28	1.003 23	3.277 93	—
0.20	1.008 00	1.028 28	1.020 12	1.003 99	2.963 52	—
0.22	1.009 68	1.034 29	1.024 38	1.004 83	2.707 60	—
0.24	1.011 52	1.040 90	1.029 05	1.005 74	2.495 56	—
0.26	1.013 52	1.048 13	1.034 14	1.006 74	2.317 29	—
0.28	1.015 68	1.055 96	1.039 66	1.007 81	2.165 55	—
0.30	1.018 00	1.064 43	1.045 61	1.008 96	2.035 07	—
0.32	1.020 48	1.073 53	1.051 99	1.010 19	1.921 85	—
0.34	1.023 12	1.083 29	1.058 81	1.011 49	1.822 88	—
0.36	1.025 92	1.093 70	1.066 07	1.012 88	1.735 78	—
0.38	1.028 88	1.104 78	1.073 77	1.014 34	1.658 70	—
0.40	1.032 00	1.116 55	1.081 93	1.015 87	1.590 14	—
0.42	1.035 28	1.129 02	1.090 55	1.017 49	1.528 91	—
0.44	1.038 72	1.142 21	1.099 63	1.019 18	1.474 01	—
0.46	1.042 32	1.156 12	1.109 18	1.020 94	1.424 63	—
0.48	1.046 08	1.170 78	1.119 21	1.022 78	1.380 10	—
0.50	1.050 00	1.186 21	1.129 73	1.024 70	1.339 84	—
0.52	1.054 08	1.202 42	1.140 73	1.026 68	1.303 39	—
0.54	1.058 32	1.219 44	1.152 24	1.028 75	1.270 32	—
0.56	1.062 72	1.237 27	1.164 25	1.030 88	1.240 29	—
0.58	1.067 28	1.255 96	1.176 78	1.033 09	1.213 01	—
0.60	1.072 00	1.275 50	1.189 84	1.035 37	1.188 20	—
0.62	1.076 88	1.295 94	1.203 42	1.037 73	1.165 65	—
0.64	1.081 92	1.317 29	1.217 55	1.040 15	1.145 15	—

M	T_0/T	p_0/p	ρ_0/ρ	a_0/a	A/A^*	θ
0.66	1.087 12	1.339 59	1.232 24	1.042 65	1.126 54	—
0.68	1.092 48	1.362 85	1.247 48	1.045 22	1.109 66	—
0.70	1.098 00	1.387 10	1.263 30	1.047 85	1.094 37	—
0.72	1.103 68	1.412 38	1.279 70	1.050 56	1.080 57	—
0.74	1.109 52	1.438 71	1.296 69	1.053 34	1.068 14	—
0.76	1.115 52	1.466 12	1.314 30	1.056 18	1.057 00	—
0.78	1.121 68	1.494 66	1.332 52	1.059 09	1.047 05	—
0.80	1.128 00	1.524 34	1.351 36	1.062 07	1.038 23	—
0.82	1.134 48	1.555 21	1.370 86	1.065 12	1.030 46	—
0.84	1.141 12	1.587 30	1.391 00	1.068 23	1.023 70	—
0.86	1.147 92	1.620 65	1.411 82	1.071 41	1.017 87	—
0.88	1.154 88	1.655 31	1.433 32	1.074 65	1.012 94	—
0.90	1.162 00	1.691 30	1.455 51	1.077 96	1.008 86	—
0.92	1.169 28	1.728 68	1.478 41	1.081 33	1.005 60	—
0.94	1.176 72	1.767 48	1.502 04	1.084 77	1.003 11	—
0.96	1.184 32	1.807 76	1.526 41	1.088 26	1.001 36	—
0.98	1.192 08	1.849 56	1.551 54	1.091 82	1.000 34	—
1.00	1.200 00	1.892 93	1.577 44	1.095 44	1.000 00	—
1.02	1.208 08	1.937 91	1.604 13	1.099 13	1.000 33	0.125 68
1.04	1.216 32	1.984 57	1.631 62	1.102 87	1.001 30	0.350 97
1.06	1.224 72	2.032 96	1.659 94	1.106 67	1.002 91	0.636 68
1.08	1.233 28	2.083 13	1.689 09	1.110 53	1.005 12	0.968 03
1.10	1.242 00	2.135 13	1.719 11	1.114 45	1.007 93	1.336 19
1.12	1.250 88	2.189 04	1.750 00	1.118 43	1.011 31	1.735 03
1.14	1.259 92	2.244 92	1.781 79	1.122 46	1.015 27	2.159 94
1.16	1.269 12	2.302 81	1.814 50	1.126 55	1.019 78	2.607 33
1.18	1.278 48	2.362 81	1.848 14	1.130 70	1.024 84	3.074 24
1.20	1.288 00	2.424 96	1.882 74	1.134 90	1.030 44	3.558 22
1.22	1.297 68	2.489 35	1.918 31	1.139 16	1.036 57	4.057 18
1.24	1.307 52	2.556 05	1.954 88	1.143 47	1.043 23	4.569 34
1.26	1.317 52	2.625 12	1.992 47	1.147 83	1.050 41	5.093 13
1.28	1.327 68	2.696 66	2.031 11	1.152 25	1.058 10	5.627 17
1.30	1.338 00	2.770 74	2.070 81	1.156 72	1.066 30	6.170 26
1.32	1.348 48	2.847 44	2.111 60	1.161 24	1.075 02	6.721 31
1.34	1.359 12	2.926 86	2.153 50	1.165 81	1.084 24	7.279 34
1.36	1.369 92	3.009 07	2.196 53	1.170 44	1.093 96	7.843 48
1.38	1.380 88	3.094 18	2.240 73	1.175 11	1.104 19	8.412 94
1.40	1.392 00	3.182 27	2.286 11	1.179 83	1.114 93	8.987 00
1.42	1.403 28	3.273 44	2.332 71	1.184 60	1.126 16	9.564 99
1.44	1.414 72	3.367 80	2.380 54	1.189 42	1.137 90	10.146 33
1.46	1.426 32	3.465 44	2.429 64	1.194 29	1.150 15	10.730 47
1.48	1.438 08	3.566 48	2.480 03	1.199 20	1.162 90	11.316 91
1.50	1.450 00	3.671 03	2.531 74	1.204 16	1.176 17	11.905 18
1.52	1.462 08	3.779 19	2.584 80	1.209 16	1.189 94	12.494 86
1.54	1.474 32	3.891 08	2.639 24	1.214 22	1.204 23	13.085 57
1.56	1.486 72	4.006 83	2.695 08	1.219 31	1.219 04	13.676 93
1.58	1.499 28	4.126 57	2.752 37	1.224 45	1.234 38	14.268 62
1.60	1.512 00	4.250 41	2.811 12	1.229 63	1.250 23	14.860 32
1.62	1.524 88	4.378 49	2.871 37	1.234 86	1.266 62	15.451 77
1.64	1.537 92	4.510 94	2.933 15	1.240 13	1.283 55	16.042 68
1.66	1.551 12	4.647 91	2.996 49	1.245 44	1.301 02	16.632 82
1.68	1.564 48	4.789 54	3.061 43	1.250 79	1.319 04	17.221 95
1.70	1.578 00	4.935 98	3.128 00	1.256 18	1.337 61	17.809 88

M	T_0/T	p_0/p	ρ_0/ρ	a_0/a	A/A^*	θ
1.72	1.591 68	5.087 38	3.196 24	1.261 62	1.356 73	18.396 40
1.74	1.605 52	5.243 90	3.266 17	1.267 09	1.376 43	18.981 34
1.76	1.619 52	5.405 69	3.337 84	1.272 60	1.396 70	19.564 53
1.78	1.633 68	5.572 93	3.411 28	1.278 15	1.417 54	20.145 80
1.80	1.648 00	5.745 78	3.486 52	1.283 74	1.438 98	20.725 03
1.82	1.662 48	5.924 43	3.563 61	1.289 37	1.461 01	21.302 08
1.84	1.677 12	6.109 05	3.642 58	1.295 04	1.483 65	21.876 82
1.86	1.691 92	6.299 82	3.723 48	1.300 74	1.506 89	22.449 14
1.88	1.706 88	6.496 95	3.806 33	1.306 48	1.530 76	23.018 93
1.90	1.722 00	6.700 62	3.891 19	1.312 25	1.555 25	23.586 10
1.92	1.737 28	6.911 04	3.978 08	1.318 06	1.580 39	24.150 56
1.94	1.752 72	7.128 41	4.067 06	1.323 90	1.606 17	24.712 23
1.96	1.768 32	7.352 96	4.158 16	1.329 78	1.632 61	25.271 02
1.98	1.784 08	7.584 89	4.251 43	1.335 69	1.659 71	25.826 88
2.00	1.800 00	7.824 43	4.346 91	1.341 64	1.687 50	26.379 73
2.02	1.816 08	8.071 82	4.444 64	1.347 62	1.715 97	26.929 52
2.04	1.832 32	8.327 29	4.544 67	1.353 63	1.745 14	27.476 19
2.06	1.848 72	8.591 09	4.647 05	1.359 68	1.775 01	28.019 70
2.08	1.865 28	8.863 46	4.751 81	1.365 75	1.805 61	28.560 00
2.10	1.882 00	9.144 66	4.859 02	1.371 86	1.836 94	29.097 05
2.12	1.898 88	9.434 97	4.968 70	1.378 00	1.869 01	29.630 82
2.14	1.915 92	9.734 64	5.080 92	1.384 17	1.901 84	30.161 27
2.16	1.933 12	10.043 96	5.195 73	1.390 37	1.935 43	30.688 38
2.18	1.950 48	10.363 21	5.313 16	1.396 60	1.969 81	31.212 12
2.20	1.968 00	10.692 68	5.433 28	1.402 85	2.004 97	31.732 47
2.22	1.985 68	11.032 69	5.556 13	1.409 14	2.040 94	32.249 40
2.24	2.003 52	11.383 52	5.681 77	1.415 46	2.077 73	32.762 91
2.26	2.021 52	11.745 51	5.810 24	1.421 80	2.115 35	33.272 98
2.28	2.039 68	12.118 98	5.941 61	1.428 17	2.153 81	33.779 61
2.30	2.058 00	12.504 25	6.075 93	1.434 57	2.193 13	34.282 76
2.32	2.076 48	12.901 67	6.213 25	1.441 00	2.233 32	34.782 46
2.34	2.095 12	13.311 59	6.353 62	1.447 45	2.274 40	35.278 68
2.36	2.113 92	13.734 37	6.497 11	1.453 93	2.316 38	35.771 43
2.38	2.132 88	14.170 37	6.643 78	1.460 44	2.359 27	36.260 70
2.40	2.152 00	14.619 98	6.793 68	1.466 97	2.403 10	36.746 50
2.42	2.171 28	15.083 57	6.946 86	1.473 53	2.447 87	37.228 83
2.44	2.190 72	15.561 55	7.103 40	1.480 11	2.493 60	37.707 69
2.46	2.210 32	16.054 32	7.263 35	1.486 71	2.540 31	38.183 09
2.48	2.230 08	16.562 28	7.426 77	1.493 34	2.588 01	38.655 04
2.50	2.250 00	17.085 89	7.593 73	1.500 00	2.636 71	39.123 54
2.52	2.270 08	17.625 55	7.764 29	1.506 68	2.686 45	39.588 59
2.54	2.290 32	18.181 74	7.938 52	1.513 38	2.737 22	40.050 23
2.56	2.310 72	18.754 88	8.116 47	1.520 10	2.789 06	40.508 44
2.58	2.331 28	19.345 57	8.298 22	1.526 85	2.841 97	40.963 26
2.60	2.352 00	19.953 97	8.483 84	1.533 62	2.895 97	41.414 68
2.62	2.372 88	20.580 88	8.673 38	1.540 41	2.951 08	41.862 72
2.64	2.393 92	21.226 70	8.866 93	1.547 23	3.007 33	42.307 41
2.66	2.415 12	21.891 94	9.064 54	1.554 06	3.064 71	42.748 74
2.68	2.436 48	22.577 12	9.266 30	1.560 92	3.123 27	43.186 76
2.70	2.458 00	23.282 80	9.472 26	1.567 80	3.183 00	43.621 45
2.72	2.479 68	24.009 52	9.682 51	1.574 70	3.243 94	44.052 85
2.74	2.501 52	24.757 83	9.897 12	1.581 62	3.306 11	44.480 97
2.76	2.523 52	25.528 32	10.116 17	1.588 56	3.369 51	44.905 83

M	T_0/T	p_0/p	ρ_0/ρ	a_0/a	A/A^*	θ
2.78	2.545 68	26.321 58	10.339 71	1.595 52	3.434 17	45.327 46
2.80	2.568 00	27.138 21	10.567 85	1.602 50	3.500 12	45.745 86
2.82	2.590 48	27.978 82	10.800 64	1.609 50	3.567 36	46.161 06
2.84	2.613 12	28.844 06	11.038 18	1.616 51	3.635 93	46.573 09
2.86	2.635 92	29.734 55	11.280 53	1.623 55	3.705 83	46.981 95
2.88	2.658 88	30.650 97	11.527 78	1.630 61	3.777 11	47.387 68
2.90	2.682 00	31.593 98	11.780 02	1.637 68	3.849 76	47.790 28
2.92	2.705 28	32.564 27	12.037 31	1.644 77	3.923 82	48.189 80
2.94	2.728 72	33.562 55	12.299 75	1.651 88	3.999 31	48.586 24
2.96	2.752 32	34.589 54	12.567 42	1.659 01	4.076 25	48.979 62
2.98	2.776 08	35.645 97	12.840 41	1.666 16	4.154 65	49.369 97
3.00	2.800 00	36.732 60	13.118 80	1.673 32	4.234 56	49.757 32
3.05	2.860 50	39.586 34	13.838 97	1.691 30	4.441 01	50.712 67
3.10	2.922 00	42.646 09	14.594 84	1.709 38	4.657 30	51.649 72
3.15	2.984 50	45.924 97	15.387 84	1.727 57	4.883 82	52.568 81
3.20	3.048 00	49.436 84	16.219 45	1.745 85	5.120 95	53.470 31
3.25	3.112 50	53.196 26	17.091 19	1.764 23	5.369 08	54.354 57
3.30	3.178 00	57.218 57	18.004 60	1.782 69	5.628 63	55.221 95
3.35	3.244 50	61.519 89	18.961 31	1.801 25	5.900 02	56.072 81
3.40	3.312 00	66.117 20	19.962 94	1.819 89	6.183 68	56.907 49
3.45	3.380 50	71.028 34	21.011 22	1.838 61	6.480 06	57.726 36
3.50	3.450 00	76.272 00	22.107 85	1.857 42	6.789 60	58.529 74
3.55	3.520 50	81.867 87	23.254 64	1.876 30	7.112 79	59.317 99
3.60	3.592 00	87.836 57	24.453 42	1.895 26	7.450 09	60.091 43
3.65	3.664 50	94.199 76	25.706 06	1.914 29	7.802 01	60.850 41
3.70	3.738 00	100.980 10	27.014 50	1.933 39	8.169 05	61.595 26
3.75	3.812 50	108.201 36	28.380 72	1.952 56	8.551 72	62.326 27
3.80	3.888 00	115.888 43	29.806 73	1.971 80	8.950 56	63.043 78
3.85	3.964 49	124.067 40	31.294 63	1.991 10	9.366 12	63.748 09
3.90	4.041 99	132.765 49	32.846 52	2.010 47	9.798 95	64.439 50
3.95	4.120 49	142.011 32	34.464 62	2.029 90	10.249 62	65.118 31
4.00	4.199 99	151.834 58	36.151 13	2.049 39	10.718 72	65.784 80
4.05	4.280 50	162.266 74	37.908 39	2.068 94	11.206 86	66.439 29
4.10	4.362 00	173.340 19	39.738 71	2.088 54	11.714 64	67.082 01
4.15	4.444 50	185.088 88	41.644 47	2.108 20	12.242 69	67.713 26
4.20	4.528 00	197.548 26	43.628 13	2.127 91	12.791 66	68.333 28
4.25	4.612 50	210.755 45	45.692 19	2.147 67	13.362 19	68.942 34
4.30	4.698 01	224.748 89	47.839 20	2.167 49	13.954 95	69.540 70
4.35	4.784 51	239.568 98	50.071 81	2.187 35	14.570 63	70.128 59
4.40	4.872 01	255.257 69	52.392 68	2.207 26	15.209 95	70.706 26
4.45	4.960 51	271.858 55	54.804 52	2.227 22	15.873 59	71.273 94
4.50	5.050 01	289.417 21	57.310 17	2.247 22	16.562 31	71.831 86
4.60	5.232 02	327.599 15	62.614 28	2.287 36	18.017 96	72.919 30
4.70	5.418 02	370.205 87	68.328 57	2.327 66	19.583 04	73.970 28
4.80	5.608 03	417.672 52	74.477 59	2.368 13	21.263 98	74.986 45
4.90	5.802 03	470.468 96	81.086 90	2.408 74	23.067 45	75.969 35
5.00	6.000 04	529.101 93	88.183 07	2.449 50	25.000 39	76.920 43
5.10	6.202 04	594.117 25	95.793 76	2.490 39	27.070 04	77.841 09
5.20	6.408 05	666.102 11	103.947 69	2.531 41	29.283 89	78.732 67
5.30	6.618 06	745.687 19	112.674 64	2.572 56	31.649 71	79.596 42
5.40	6.832 06	833.549 62	122.005 55	2.613 82	34.175 57	80.433 50
5.50	7.050 07	930.415 10	131.972 47	2.655 20	36.869 84	81.245 07

APPENDIX C

Normal Shock Tables for $\gamma = 1.4$

M_1	M_2	p_2/p_1	T_2/T_1	ρ_2/ρ_1	p_{02}/p_{01}	p_{02}/p_1
1.00	1.000 00	1.000 00	1.000 00	1.000 00	1.000 00	1.892 93
1.02	0.980 52	1.047 13	1.013 25	1.033 44	0.999 99	1.937 90
1.04	0.962 03	1.095 20	1.026 34	1.067 09	0.999 92	1.984 42
1.06	0.944 45	1.144 20	1.039 31	1.100 92	0.999 75	2.032 45
1.08	0.927 71	1.194 13	1.052 17	1.134 92	0.999 43	2.081 94
1.10	0.911 77	1.245 00	1.064 94	1.169 08	0.998 93	2.132 85
1.12	0.896 56	1.296 80	1.077 63	1.203 38	0.998 21	2.185 13
1.14	0.882 04	1.349 53	1.090 27	1.237 79	0.997 26	2.238 77
1.16	0.868 16	1.403 20	1.102 87	1.272 31	0.996 05	2.293 72
1.18	0.854 88	1.457 80	1.115 44	1.306 93	0.994 57	2.349 98
1.20	0.842 17	1.513 33	1.127 99	1.341 61	0.992 80	2.407 50
1.22	0.829 99	1.569 80	1.140 54	1.376 36	0.990 73	2.466 28
1.24	0.818 30	1.627 20	1.153 09	1.411 16	0.988 36	2.526 29
1.26	0.807 09	1.685 53	1.165 66	1.445 99	0.985 68	2.587 53
1.28	0.796 31	1.744 80	1.178 25	1.480 84	0.982 68	2.649 96
1.30	0.785 96	1.805 00	1.190 87	1.515 69	0.979 37	2.713 59
1.32	0.776 00	1.866 13	1.203 53	1.550 55	0.975 75	2.778 40
1.34	0.766 41	1.928 20	1.216 24	1.585 38	0.971 82	2.844 38
1.36	0.757 18	1.991 20	1.229 00	1.620 18	0.967 58	2.911 52
1.38	0.748 29	2.055 13	1.241 81	1.654 94	0.963 04	2.979 80
1.40	0.739 71	2.120 00	1.254 69	1.689 65	0.958 19	3.049 23
1.42	0.731 44	2.185 80	1.267 64	1.724 30	0.953 06	3.119 80
1.44	0.723 45	2.252 53	1.280 66	1.758 88	0.947 65	3.191 49
1.46	0.715 74	2.320 20	1.293 76	1.793 37	0.941 96	3.264 30
1.48	0.708 29	2.388 80	1.306 95	1.827 77	0.936 00	3.338 23
1.50	0.701 09	2.458 33	1.320 22	1.862 07	0.929 79	3.413 27
1.52	0.694 13	2.528 80	1.333 57	1.896 26	0.923 32	3.489 42
1.54	0.687 39	2.600 20	1.347 03	1.930 33	0.916 62	3.566 66
1.56	0.680 87	2.672 53	1.360 57	1.964 27	0.909 70	3.645 01
1.58	0.674 55	2.745 80	1.374 22	1.998 08	0.902 55	3.724 44
1.60	0.668 44	2.820 00	1.387 97	2.031 75	0.895 20	3.804 97

M_1	M_2	p_2/p_1	T_2/T_1	ρ_2/ρ_1	p_{02}/p_{01}	p_{02}/p_1
1.62	0.662 51	2.895 13	1.401 82	2.065 26	0.887 65	3.886 58
1.64	0.656 77	2.971 20	1.415 78	2.098 63	0.879 92	3.969 28
1.66	0.651 19	3.048 20	1.429 85	2.131 83	0.872 01	4.053 05
1.68	0.645 79	3.126 13	1.444 03	2.164 86	0.863 94	4.137 90
1.70	0.640 54	3.205 00	1.458 33	2.197 72	0.855 72	4.223 83
1.72	0.635 45	3.284 80	1.472 74	2.230 40	0.847 36	4.310 83
1.74	0.630 51	3.365 53	1.487 27	2.262 89	0.838 86	4.398 90
1.76	0.625 70	3.447 20	1.501 92	2.295 20	0.830 24	4.488 04
1.78	0.621 04	3.529 80	1.516 69	2.327 31	0.821 51	4.578 24
1.80	0.616 50	3.613 33	1.531 58	2.359 22	0.812 68	4.669 51
1.82	0.612 09	3.697 80	1.546 59	2.390 93	0.803 76	4.761 84
1.84	0.607 80	3.783 20	1.561 73	2.422 44	0.794 76	4.855 24
1.86	0.603 63	3.869 53	1.577 00	2.453 73	0.785 69	4.949 69
1.88	0.599 57	3.956 80	1.592 39	2.484 81	0.776 55	5.045 20
1.90	0.595 62	4.045 00	1.607 91	2.515 68	0.767 36	5.141 77
1.92	0.591 77	4.134 13	1.623 57	2.546 32	0.758 12	5.239 40
1.94	0.588 02	4.224 20	1.639 35	2.576 75	0.748 84	5.338 08
1.96	0.584 37	4.315 20	1.655 27	2.606 95	0.739 54	5.437 81
1.98	0.580 82	4.407 13	1.671 32	2.636 92	0.730 21	5.538 60
2.00	0.577 35	4.500 00	1.687 50	2.666 67	0.720 87	5.640 44
2.02	0.573 97	4.593 80	1.703 82	2.696 18	0.711 53	5.743 32
2.04	0.570 68	4.688 53	1.720 27	2.725 46	0.702 18	5.847 26
2.06	0.567 47	4.784 19	1.736 86	2.754 51	0.692 84	5.952 25
2.08	0.564 33	4.880 80	1.753 59	2.783 32	0.683 51	6.058 29
2.10	0.561 28	4.978 33	1.770 45	2.811 90	0.674 20	6.165 37
2.12	0.558 29	5.076 79	1.787 45	2.840 24	0.664 92	6.273 50
2.14	0.555 38	5.176 19	1.804 59	2.868 34	0.655 67	6.382 68
2.16	0.552 54	5.276 53	1.821 87	2.896 21	0.646 45	6.492 90
2.18	0.549 77	5.377 79	1.839 30	2.923 83	0.637 27	6.604 16
2.20	0.547 06	5.479 99	1.856 86	2.951 22	0.628 14	6.716 47
2.22	0.544 41	5.583 13	1.874 56	2.978 36	0.619 05	6.829 83
2.24	0.541 82	5.687 19	1.892 41	3.005 27	0.610 02	6.944 23
2.26	0.539 30	5.792 19	1.910 40	3.031 93	0.601 05	7.059 67
2.28	0.536 83	5.898 13	1.928 53	3.058 36	0.592 14	7.176 15
2.30	0.534 41	6.004 99	1.946 80	3.084 55	0.583 30	7.293 67
2.32	0.532 05	6.112 79	1.965 22	3.110 49	0.574 52	7.412 24
2.34	0.529 74	6.221 53	1.983 78	3.136 20	0.565 81	7.531 84
2.36	0.527 49	6.331 19	2.002 48	3.161 67	0.557 18	7.652 49
2.38	0.525 28	6.441 79	2.021 33	3.186 90	0.548 62	7.774 18
2.40	0.523 12	6.553 33	2.040 33	3.211 89	0.540 14	7.896 91
2.42	0.521 00	6.665 79	2.059 47	3.236 65	0.531 75	8.020 67
2.44	0.518 94	6.779 19	2.078 76	3.261 17	0.523 44	8.145 48
2.46	0.516 91	6.893 53	2.098 19	3.285 46	0.515 21	8.271 32
2.48	0.514 93	7.008 79	2.117 77	3.309 51	0.507 07	8.398 21
2.50	0.512 99	7.124 99	2.137 50	3.333 33	0.499 02	8.526 13
2.52	0.511 09	7.242 12	2.157 37	3.356 92	0.491 05	8.655 09
2.54	0.509 23	7.360 19	2.177 39	3.380 28	0.483 18	8.785 08
2.56	0.507 41	7.479 19	2.197 56	3.403 41	0.475 40	8.916 12
2.58	0.505 62	7.599 12	2.217 88	3.426 31	0.467 72	9.048 19
2.60	0.503 87	7.719 99	2.238 34	3.448 98	0.460 12	9.181 30
2.62	0.502 16	7.841 79	2.258 95	3.471 43	0.452 63	9.315 44
2.64	0.500 48	7.964 52	2.279 71	3.493 65	0.445 22	9.450 63
2.66	0.498 83	8.088 19	2.300 62	3.515 65	0.437 92	9.586 84

M_1	M_2	p_2/p_1	T_2/T_1	ρ_2/ρ_1	p_{02}/p_{01}	p_{02}/p_1
2.68	0.497 22	8.212 79	2.321 68	3.537 43	0.430 71	9.724 10
2.70	0.495 63	8.338 32	2.342 89	3.558 99	0.423 59	9.862 39
2.72	0.494 08	8.464 79	2.364 25	3.580 33	0.416 57	10.001 71
2.74	0.492 56	8.592 19	2.385 75	3.601 46	0.409 65	10.142 08
2.76	0.491 07	8.720 52	2.407 41	3.622 37	0.402 83	10.283 47
2.78	0.489 60	8.849 79	2.429 22	3.643 06	0.396 10	10.425 91
2.80	0.488 17	8.979 99	2.451 17	3.663 55	0.389 46	10.569 37
2.82	0.486 76	9.111 12	2.473 28	3.683 83	0.382 93	10.713 88
2.84	0.485 38	9.243 19	2.495 53	3.703 89	0.376 49	10.859 41
2.86	0.484 02	9.376 19	2.517 94	3.723 75	0.370 14	11.005 99
2.88	0.482 69	9.510 12	2.540 50	3.743 41	0.363 89	11.153 59
2.90	0.481 38	9.644 99	2.563 21	3.762 86	0.357 73	11.302 23
2.92	0.480 10	9.780 79	2.586 06	3.782 11	0.351 67	11.451 91
2.94	0.478 84	9.917 52	2.609 07	3.801 17	0.345 70	11.602 62
2.96	0.477 60	10.055 19	2.632 23	3.820 02	0.339 82	11.754 36
2.98	0.476 38	10.193 79	2.655 55	3.838 68	0.334 04	11.907 14
3.00	0.475 19	10.333 32	2.679 01	3.857 14	0.328 34	12.060 95
3.05	0.472 30	10.686 24	2.738 33	3.902 46	0.314 50	12.450 00
3.10	0.469 53	11.044 99	2.798 60	3.946 61	0.301 21	12.845 51
3.15	0.466 89	11.409 57	2.859 82	3.989 61	0.288 46	13.247 48
3.20	0.464 35	11.779 98	2.921 99	4.031 49	0.276 23	13.655 90
3.25	0.461 92	12.156 23	2.985 11	4.072 29	0.264 51	14.070 78
3.30	0.459 59	12.538 32	3.049 19	4.112 02	0.253 28	14.492 12
3.35	0.457 35	12.926 23	3.114 22	4.150 71	0.242 52	14.919 91
3.40	0.455 20	13.319 98	3.180 20	4.188 40	0.232 23	15.354 15
3.45	0.453 14	13.719 56	3.247 15	4.225 11	0.222 37	15.794 84
3.50	0.451 15	14.124 98	3.315 05	4.260 87	0.212 95	16.241 98
3.55	0.449 25	14.536 23	3.383 91	4.295 70	0.203 93	16.695 57
3.60	0.447 41	14.953 31	3.453 72	4.329 62	0.195 31	17.155 61
3.65	0.445 65	15.376 23	3.524 50	4.362 67	0.187 07	17.622 10
3.70	0.443 95	15.804 98	3.596 24	4.394 86	0.179 19	18.095 04
3.75	0.442 31	16.239 56	3.668 94	4.426 23	0.171 67	18.574 43
3.80	0.440 73	16.679 98	3.742 60	4.456 79	0.164 47	19.060 26
3.85	0.439 21	17.126 22	3.817 22	4.486 57	0.157 60	19.552 54
3.90	0.437 74	17.578 31	3.892 81	4.515 58	0.151 03	20.051 26
3.95	0.436 33	18.036 22	3.969 36	4.543 86	0.144 75	29.556 44
4.00	0.434 96	18.499 97	4.046 87	4.571 43	0.138 76	21.068 05
4.05	0.433 64	18.969 57	4.125 35	4.598 29	0.133 03	21.586 12
4.10	0.432 36	19.444 99	4.204 79	4.624 48	0.127 56	22.110 64
4.15	0.431 13	19.926 26	4.285 20	4.650 02	0.122 33	22.641 61
4.20	0.429 94	20.413 35	4.366 57	4.674 91	0.117 33	23.179 01
4.25	0.428 78	20.906 28	4.448 91	4.699 19	0.112 56	23.722 86
4.30	0.427 67	21.405 04	4.532 22	4.722 86	0.108 00	24.273 16
4.35	0.426 59	21.909 64	4.616 49	4.745 95	0.103 64	24.829 90
4.40	0.425 54	22.420 06	4.701 73	4.768 48	0.099 48	25.393 08
4.45	0.424 53	22.936 33	4.787 93	4.790 45	0.095 50	25.962 70
4.50	0.423 55	23.458 42	4.875 10	4.811 88	0.091 70	26.538 76
4.60	0.421 68	24.520 12	5.052 34	4.853 22	0.084 59	27.710 22
4.70	0.419 92	25.605 14	5.233 46	4.892 59	0.078 08	28.907 45
4.80	0.418 26	26.713 51	5.418 45	4.930 11	0.072 14	30.130 45
4.90	0.416 70	27.845 20	5.607 30	4.965 88	0.066 70	31.379 21
5.00	0.415 23	29.000 23	5.800 04	5.000 01	0.061 72	32.653 73

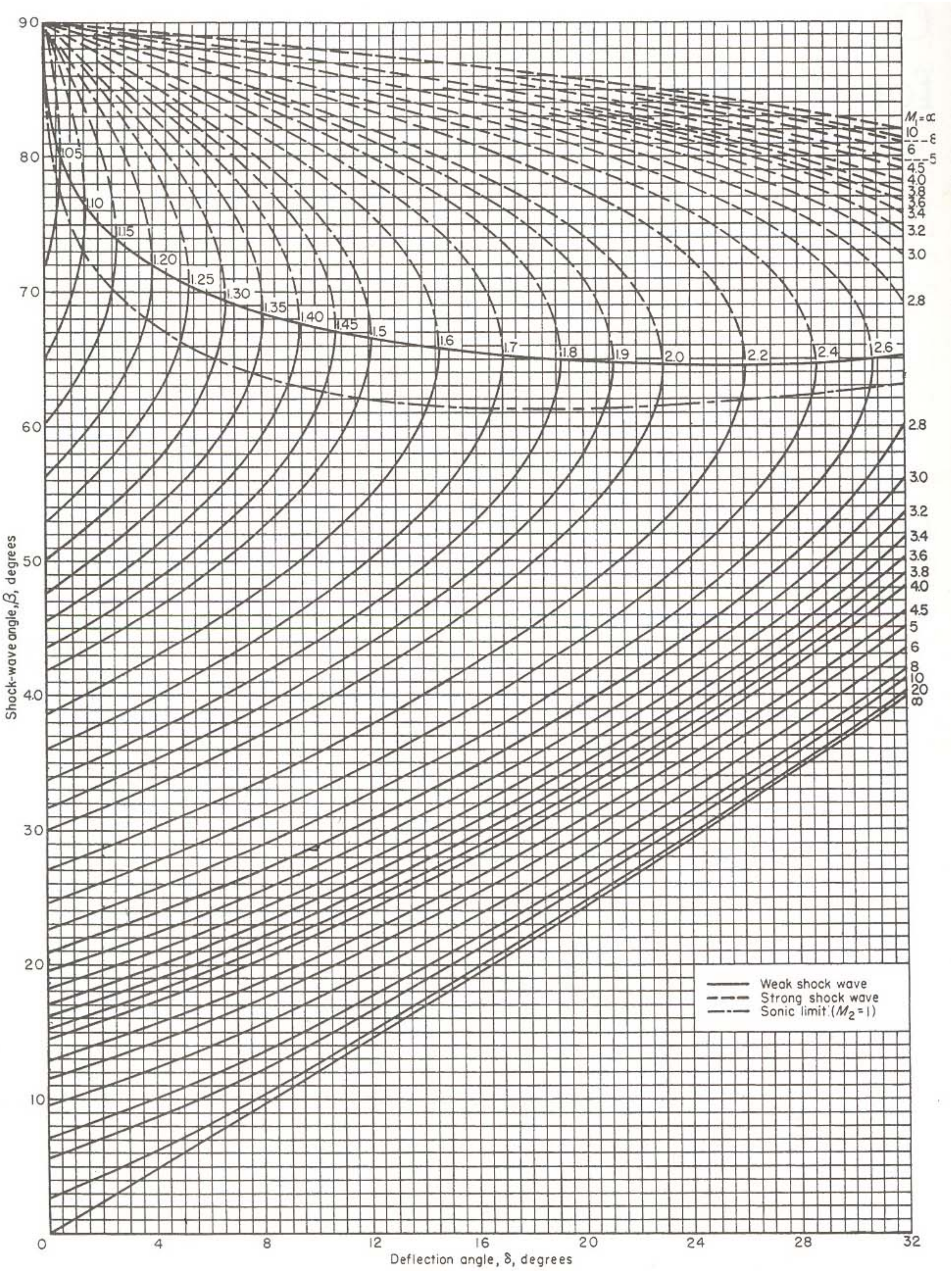

FIGURE G1
Variation of oblique shock wave angle with flow deflection angle for various upstream Mach numbers.

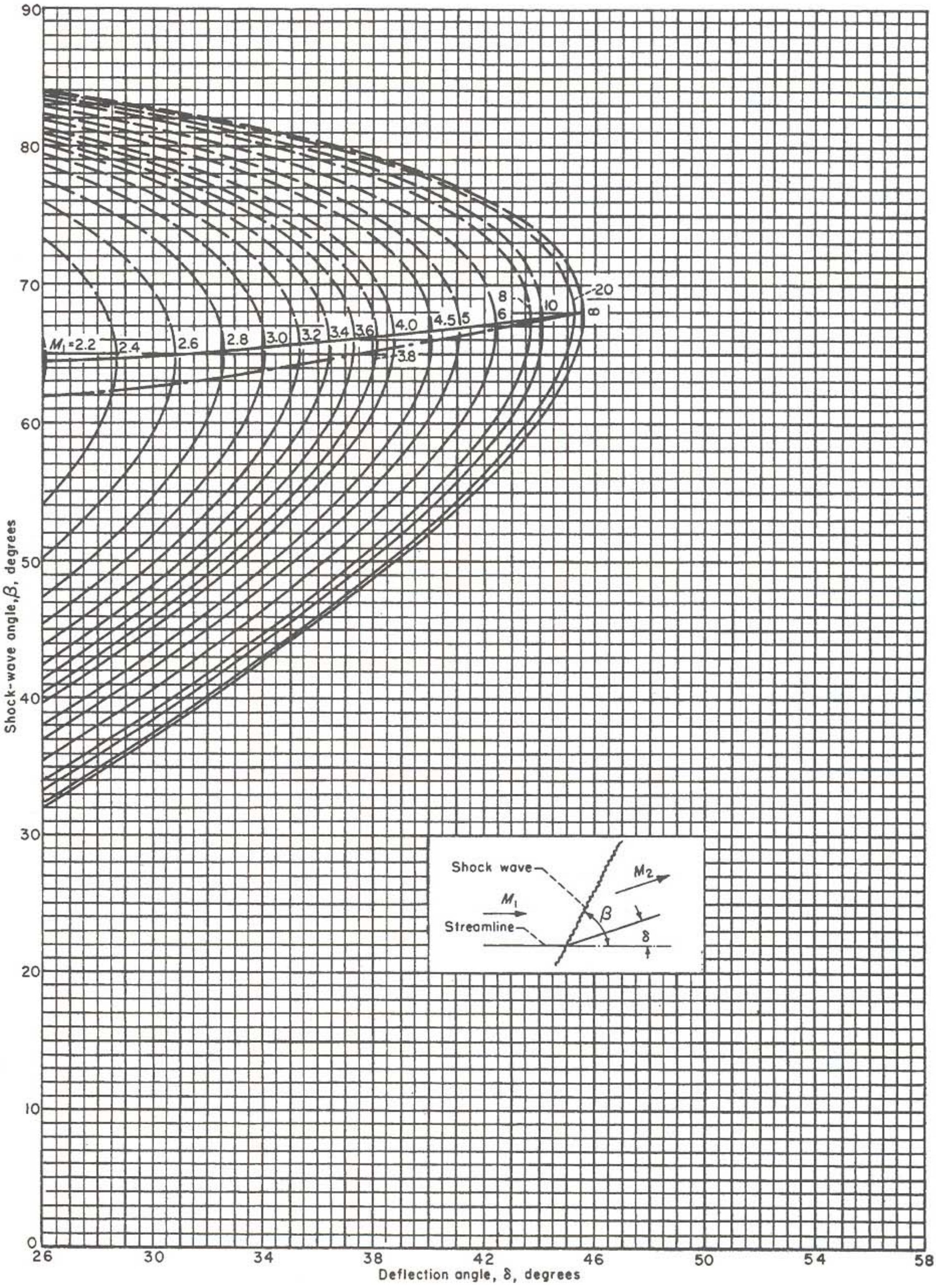

FIGURE G1 *(continued)*

ooo000ooo