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DESIGN CRITERIA, TRAJECTORIES, AND HEATING RATES FOR THE APOLLO COMMAND MODULE HEAT SHIELD VOLUME I (U)

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1.0 SCOPE

This report contains the aerodynamic and thermal data required for the design of the Apollo command module heat shield. All figure numbers refer to Volume I.

2.0 DETAIL DATA

2.1 COMMAND MODULE REFERENCE POINTS

Figures 1 and 2 show the definition of the points on the command module exterior surface used in defining heating rates.

2.2 TRAJECTORIES

Figures 3 through 23 define the trajectories for which the thermal protection system is to be designed. These trajectories are as follows:

2.2.1 Boost Trajectories

1. Saturn V lunar orbital rendezvous (LOR) boost trajectory (HSB-1). (Three stage to translunar injection via 100 NM parking orbit, Figures 3 and 4.) This trajectory represents the most severe apex forward aerodynamic heating condition during atmospheric exit without abort.

2. Saturn I boost trajectory (HSB-2). (100 NM orbital altitude, manned spacecraft, Figures 5 and 6.) This trajectory is a reference for LES abort data and establishes the initial flight conditions for abort initiation.

2.2.2 Launch Escape System (LES) Aborts During Boost

1. Maximum dynamic pressure abort. (Trajectory HSA-1, Figure 7.) This trajectory corresponds to apex forward trim during tower-on operation and aft compartment forward following tower jettison.

2. Maximum altitude for LES abort. (Tumbling LES Configuration-trajectory HSA-3, Figure 8.) This trajectory corresponds to

[redacted]

unstable (tumbling) flight during tower-on operation and an aft compartment forward condition following tower jettison.

2.2.3 Entry Trajectories (L/D = 0.5)

1. Satellite speed entries

   a. Maximum heating load (Trajectory HSE-1, Figures 9, 10 and 11)

   b. Maximum heating rate (Trajectory HSE-2, Figures 9, 12 and 13)

2. Escape speed entries

   a. Maximum supercircular speed heating load combined with maximum subcircular speed heating load (Trajectory HSE-3A, Figures 14 through 16)

   b. Maximum supercircular speed heating rate combined with maximum subcircular heating load (Trajectory HSE-4A, Figures 14, 17 and 18)

   c. Minimum heating time (Structural limit) (Trajectory HSE-6, Figures 14, 19 and 20)

2.2.4 Recovery Trajectories

1. Maximum descent time (Trajectory HSR-1, Figure 21)

2. Minimum descent time (Trajectory HSR-2, Figure 22)

2.3 HEATING RATES

Heating rates are given for the command module heat shield for launch, abort, and entry phases (escape and earth orbital speeds). Heating rates to surface discontinuities, and the effect of these discontinuities on the heat-shield heating rates are also included.

2.3.1 Launch Phase

Aerodynamic heating rates at 35 specified body points on the command module are shown in Figures 23 through 34 as a function of time for four wall temperatures. Figures 23 through 28 show heating rates for the Saturn I trajectory and Figures 29 through 34 for Saturn V. Heating rates at $X_c = 16.5$ for either trajectory are 80 percent of those at $X_c = 20$ and the corresponding meridian plane.

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2.3.2 Abort Phase

Heating rates to the specified body points of the command module are listed in Table 1 for that part of the abort phase during which the LES is fired. These rates are due to the impingement of the LES rocket plume. During LES abort analysis these rates will be applied in lieu of the boost aerodynamic heating beginning at t = 144 seconds for the Saturn I boost trajectory. This is the reference trajectory for LES abort data. The values shown in Table 1 should be applied for a total time period of five seconds (t = 144 to t = 149 seconds).

After LES rocket burnout (t = 149 seconds) heating rates are assumed to be equal to zero and remain there until t = 175 seconds. The next part of the abort phase is entry from an altitude of 400,000 feet. Heating rates are shown for various wall temperatures in Volume VII, Part A. These values apply to the time period from t = 175 to t = 390 seconds, and are based on Trajectory HSA-3.

Heating rates are assumed to vary linearly with time from the value at t = 390 seconds to zero at time of drogue chute deployment (altitude = 25,000 feet), and will remain at a value of zero until impact.

Table 1. LES Abort Plume Impingement Heating Rates

Body Points	Heating Rates (Btu/ft^2 sec)
11	40.0
10, 33, 15, 35, 19	36.5
8, 13, 17	32.3
7	30.9
6, 32, 12, 34, 16	30.8

2.3.3 Entry Phase

Convective heating rates to specified body points (excluding the wake region) of the command module during entry are graphically shown in Volumes II through VI. Five trajectories are included, each at two assumed wall temperatures (500 R and 5000 R). In all cases the curve with the higher

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values of heating rates represents a wall temperature of 500 R. The effects of aerodynamic strakes and other surface discontinuities are not included in these curves. The curves may be found in the following volumes:

Trajectory	Description	Enclosure
HSE-1	Satellitic Speed 2 g Entry (overshoot)	Volume II Part A
HSE-2	Satellitic Speed 20 g Entry (emergency)	Volume III Part A
HSE-3A	Escape Speed 2 g Entry (overshoot)	Volume IV Part A
HSE-4A	Escape Speed 10 g Entry (undershoot)	Volume V Part A
HSE-6	Escape Speed 20 g Entry (emergency)	Volume VI Part A

Heating rate histories terminate before the time of drogue chute deployment. To determine the heating rates during the time from curve termination to drogue chute deployment, a linear interpolation (in time) should be made between the final plotted value and zero at chute deployment. The drogue chute is deployed at an altitude of 25,000 feet. The corresponding time may be determined by inspection of the appropriate recovery trajectory.

Transition from laminar to turbulent flow on the attached flow region of the body is based upon a wetted length Reynolds number of 150,000. The time of transition for each specified body point is tabulated in Table 2.

2.3.3.1 Wake Region

Aerodynamic heating rates in the separated wake region are presented in graphical form in Figure 35. The two curves represent distributions along the 135- and 180-degree meridians in the form of ratios of local heating rates to the heating rates on the 90-degree meridian. A transition Reynolds

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Table 2. Apollo Entry Aerodynamic Heating—Times of Transition From Laminar to Turbulent Flow

Body Point Number	HSE-1	HSE-2	HSA-3	Body Point Number	HSE-1	HSE-2	HSA-3	Body Point Number	HSE-3A	HSE-4A	HSE-6	Body Point Number	HSE-3A	HSE-4A	HSE-6
1	—	—	—	32	2220	105	285	1	—	—	140	32	1430	1500	105
2	—	115	295	33	2180	100	285	2	—	—	130	33	1390	1470	75
3	2160	90	280	34	2220	115	290	3	1380	1455	45	34	1440	—	110
4	2060	80	275	35	2040	80	270	4	1280	60	40	35	1270	1280	40
5	2060	80	275	36	2240	105	290	5	1280	60	40	36	1470		105
6	2240	115	290	37	—	—	—	6	1470	—	120	37	1440	1500	80
7	2200	110	290	38	—	—	—	7	1460	—	115	38	1420	1485	50
8	2200	105	285	39	2200	95	285	8	1430	—	100	39	1430	1490	50
9	2220	100	285	40	—	—	—	9	1420	1480	80	40	1380	1455	45
10	2180	100	285	41	2080	85	275	10	1410	1480	80	41	1300	60	40
11	2180	100	285	42	2120	90	275	11	1400	1470	75	42	1340	60	40
12	2220	115	290	43	2200	105	285	12	1440	—	110	43	1430	1490	105
13	2040	80	270	44	2200	105	285	13	1270	1280	40	44	1420	1485	100
14	2020	80	270	45	2180	100	285	14	1250	1270	40	45	1410	1470	75
15	2040	80	270	46	2160	90	280	15	1270	1280	40	46	1380	1455	45
16	2200	105	285	47	2200	95	285	16	1420	1490	105	47	1420	1480	50
17	2040	80	270	48	2080	85	275	17	1270	1280	40	48	1310	1390	40
18	2020	80	270	49	2080	85	275	18	1250	1270	40	49	1310	1390	40
19	2040	80	270	50	2080	85	275	19	1270	1280	40	50	1310	1390	40
20	2040	80	270	51	2200	105	285	20	1250	1270	40	51	1420	1490	80
21	2040	80	270	52	2220	105	285	21	1250	1270	40	52	1440	—	100
22	2040	80	270	53	2040	80	270	22	1250	1270	40	53	1270	1280	40
23	2220	105	285	54	2180	100	285	23	1440	—	100	54	1400	1470	75
24	—	—	—	55	2200	105	285	24	1470	—	120	55	1420	1495	85
25	2240	110	290	56	2020	80	270	25	1460	—	115	56	1250	1270	40
26	—	—	—	57	2180	100	285	26	1390	1460	45	57	1400	1470	75
27	2120	85	275	58	2180	100	285	27	1350	1435	45	58	1410	1480	80
28	2080	85	275	59	2180	100	285	28	1300	60	40	59	1400	1470	75
29	—	—	—	60	2160	100	285	29	1330	60	40	60	1390	1460	75
30	2060	80	275	61	2180	100	285	30	1270	60	40	61	1410	1480	80
31	2120	90	275	62	2180	100	285	31	1350	70	40	62	1400	1470	75

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number of 20,000 was used to define turbulent flow in the separated wake region of the body. The effect of the aerodynamic strakes is not included in this figure. (See 2.3.3.2 for the effect of the strake.)

2.3.3.2 Strake Effect

The effects of the aerodynamic strakes on the surface heating rates are shown in Figures 36, 36A, and 36B. The curve shows the ratio of surface heating rate with the strake to the heating rate at the same location without the strake.

2.3.3.3 Radiative Heating Rates

Estimates of the radiative heating rates to the aft heat shield are shown as distributions in Figures 37 through 72. Equilibrium and non-equilibrium heating rates are shown for trajectories HSE-1, HSE-2, HSE-3A, HSE-4A, and HSE-6. The radiative heating rate to portions of the body not shown in this distribution is zero. There is no equilibrium radiative component for trajectory HSE-1.

Distributions are shown as ratios of the local radiative heating rate to that at body point 3. The time histories of equilibrium and non-equilibrium radiation at body point 3 are shown in Figures 73 through 81 for the five entry trajectories.

A table of S/R and X_c for the aft heat shield body points is given in Table 3. This table may be used in conjunction with the radiation distributions to locate the specified body points.

2.3.3.4 Apex Cover

Convective heating rates to the apex cover are given in Figure 82 as a ratio to the local heating at body point 24 without strakes. There is no strake effect on the apex heating.

2.3.4 Heating Rates at Surface Discontinuities

2.3.4.1 Shear Pads and Tension Tie Bolts

Perturbations in local heating rates due to the presence of shear pads and tension tie bolts on the aft heat shield are shown in Figure 83 for pad locations in Figure 83A.

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Table 3. Dimensionless Surface Distance to Body Points on Aft Heat Shield Origin Defined as Center of Aft Heat Shield (Based on Outer Mold Line)

Point Number	S/R*
1	0.967
2	0.525
3	0.0 (Reference)
4	-0.525
5	-0.967
6	1.096 (Radiation Cutoff)
12	1.096
16	-1.096
23	1.096
24	1.016
25	1.044
26	0.967
27	0.525
28	0.967
29	1.016
30	0.967
31	-1.016
32	1.096
34	-1.096
36	0.525
37	0.967
38	1.016
39	0.525
40	1.016
41	-0.525
42	-1.016
43	-1.044
44	-1.044
45	1.044
46	1.044
47	1.044

*S = the distance from the origin along the heat shield
R = radius

Figure 83 shows local heating-rate profiles, at each shear pad location, as a function of the undisturbed surface heating rate $\dot{q}_o$. Figures 84 through 89 illustrate the time history of the undisturbed surface heating rate at each shear pad location for various trajectories.

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2.3.4.2 Heating Rates in LES Tower Wells

Heating rate distributions within the LES tower wells are shown in Figures 90 and 91. These distributions are based on undisturbed surface heating rates for the cases:

1. Launch without LES tower

2. Launch with LES tower

3. Entry.

For each case, the reference heating rate is noted as being that for either body point 33 or 35. Time histories of heating rates at these reference body points are found in Figures 24 and 30 for the launch phase, and in Volumes II, III, IV, V, and VI for the entry phase.

Heating rates on the electrical umbilical in the LES tower well are presented in analogous form to that used for the LES tower wells in Figure 92.

Heating rate distributions on the strake are shown in Figure 93.

2.4 STAGNATION ENTHALPY

Stagnation enthalpies for the enclosed entry trajectories are shown graphically in Figures 94 through 99.

2.5 SHEAR STRESS

Surface aerodynamic shear stresses for the referenced body points are shown graphically for six entry trajectories. Shear stresses are based on an assumed wall temperature of 500 F.

Curves may be found in the following volumes:

Trajectory	Description	Enclosure
HSE-1	Satellitic Speed, 2 g Entry (overshoot)	Volume II Part B
HSE-2	Satellitic Speed, 20 g Entry (emergency)	Volume III Part B IV
HSE-3A	Escape Speed, 2 g Entry (overshoot)	Volume IV Part B

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Trajectory	Description	Enclosure
HSE-4A	Escape Speed, 10 g Entry (undershoot)	Volume V Part B
HSE-6	Escape Speed, 20 g Entry (emergency)	Volume VI Part B
HSA-3	Entry Following Abort	Volume VII Part B

Shear stresses (excluding the strake effect) at the body points not included in these volumes may be determined from distribution shown in Figure 35. The curve shows the ratio of local surface shear stress to the shear stress on the 90-degree meridian.

The effect of the aerodynamic strake on resultant shear stresses may be determined from Figures 36, 36A and 36B. These curves show the ratio of shear stress with the strake to shear stress without the strake.

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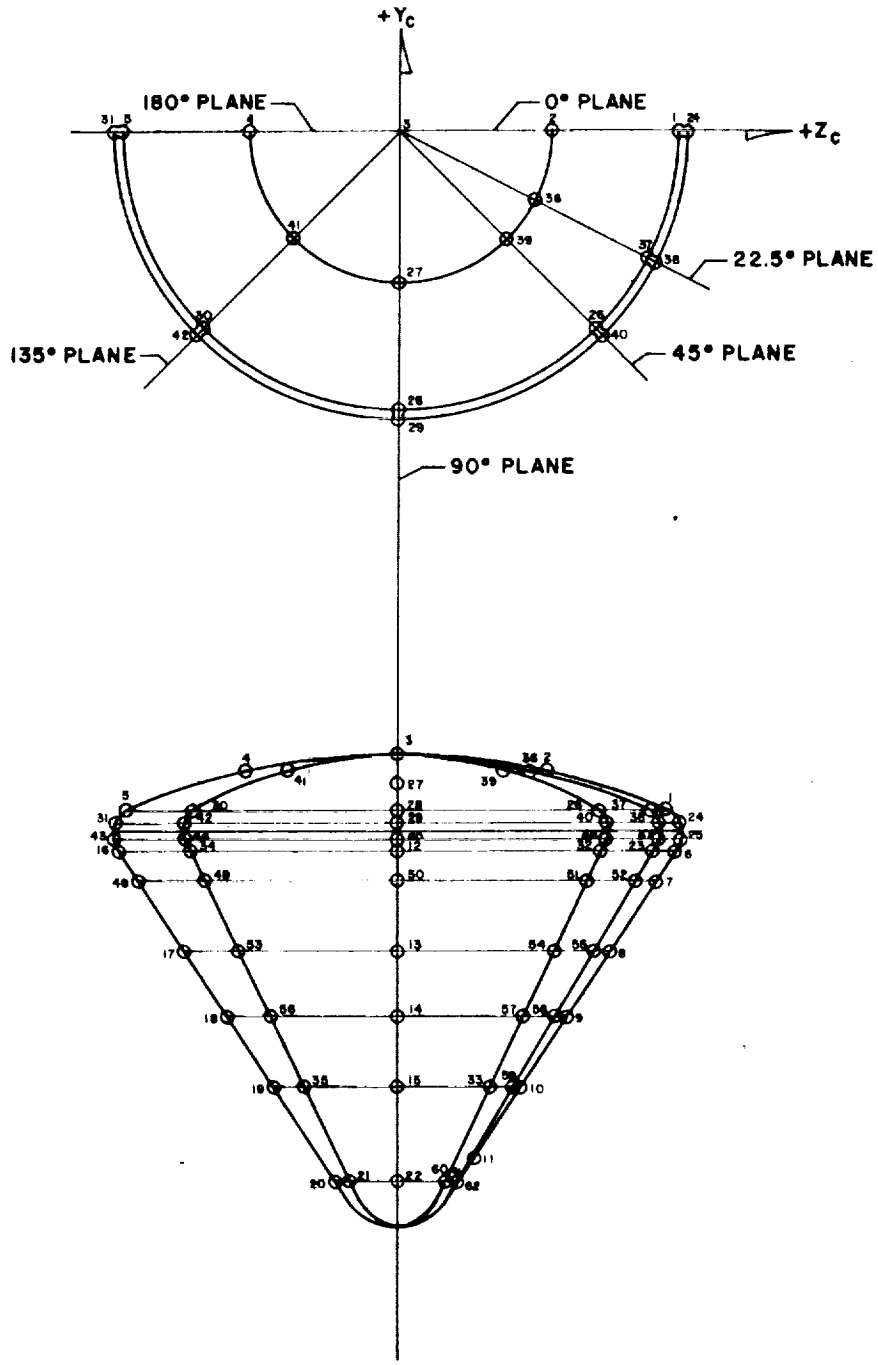

Figure 1. Apollo Entry Aerodynamic Heating, Aero-Heating Data Points

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Body Point Number	Meridian Angle λ	X_c	Body Point Number	Meridian Angle λ	X_c
1	0	15.495	31	180	18.00
2	0	4.59	32	45	23.875
3	0	0	33	45	88.00
4	180	4.59	34	135	23.875
5	180	15.495	35	135	88.00
6	0	23.875	36	22.5	4.59
7	0	30.00	37	22.5	15.495
8	0	48.00	38	22.5	18.00
9	0	68.00	39	45	4.59
10	0	88.00	40	45	18.00
11	0	107.0	41	135	4.59
12	90	23.875	42	135	18.00
13	90	48.00	43	180	20.00
14	90	68.00	44	135	20.00
15	90	88.00	45	90	20.00
16	180	23.875	46	45	20.00
17	180	48.00	47	22.5	20.00
18	180	68.00	48	180	30.00
19	180	88.00	49	135	30.00
20	180	115.347	50	90	30.00
21	135	115.347	51	45	30.00
22	90	115.347	52	22.5	30.00
23	22.5	23.875	53	135	48.00
24	0	18.00	54	45	48.00
25	0	20.00	55	22.5	48.00
26	45	15.495	56	135	68.00
27	90	4.59	57	45.	68.00
28	90	15.495	58	22.5	68.00
29	90	18.00	59	22.5	88.00
30	135	15.495	60	45	115.347
			61	22.5	115.347
			62	0	115.347

Figure 2. Apollo Entry Aerodynamic Heating, Aero-Heating Data Points

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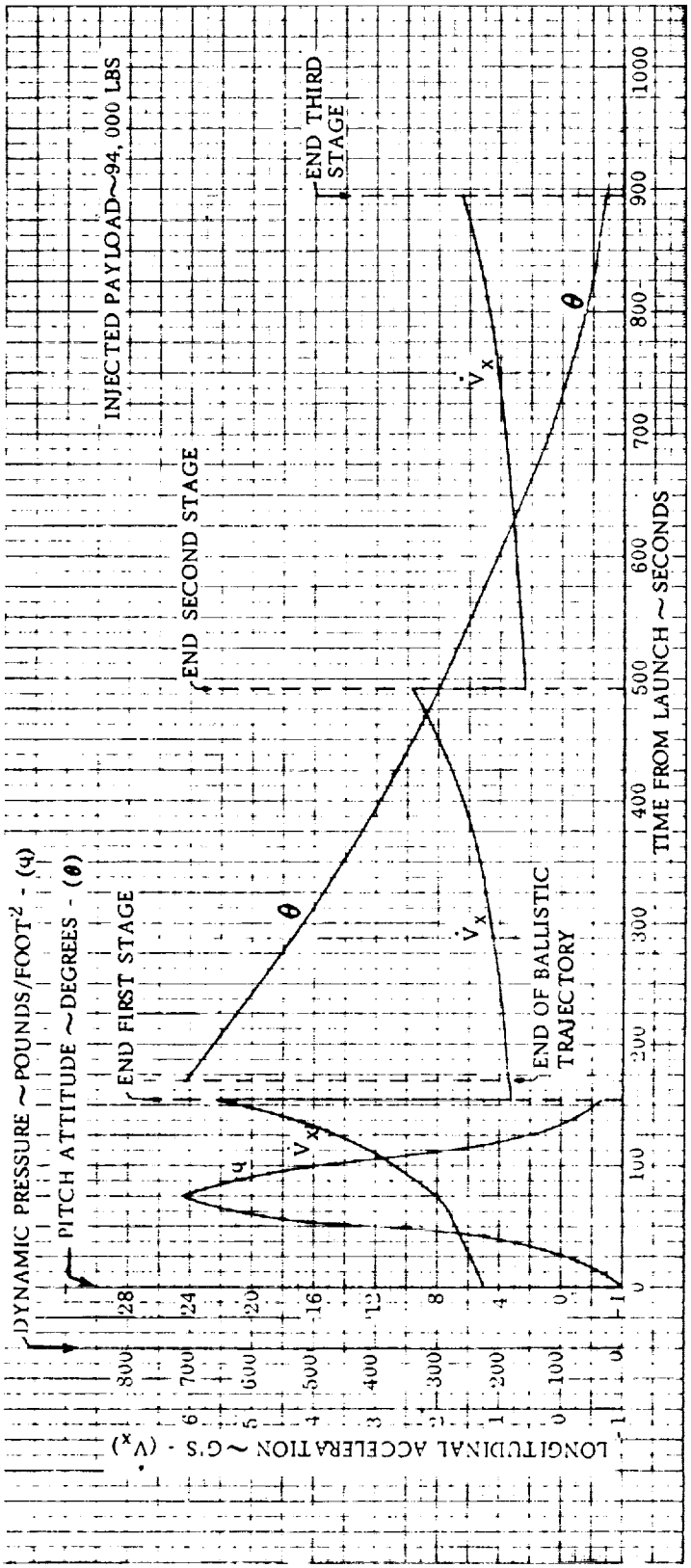

Figure 3. Saturn C-5 Nominal Boost Trajectory for Three-Stage Escape Mission

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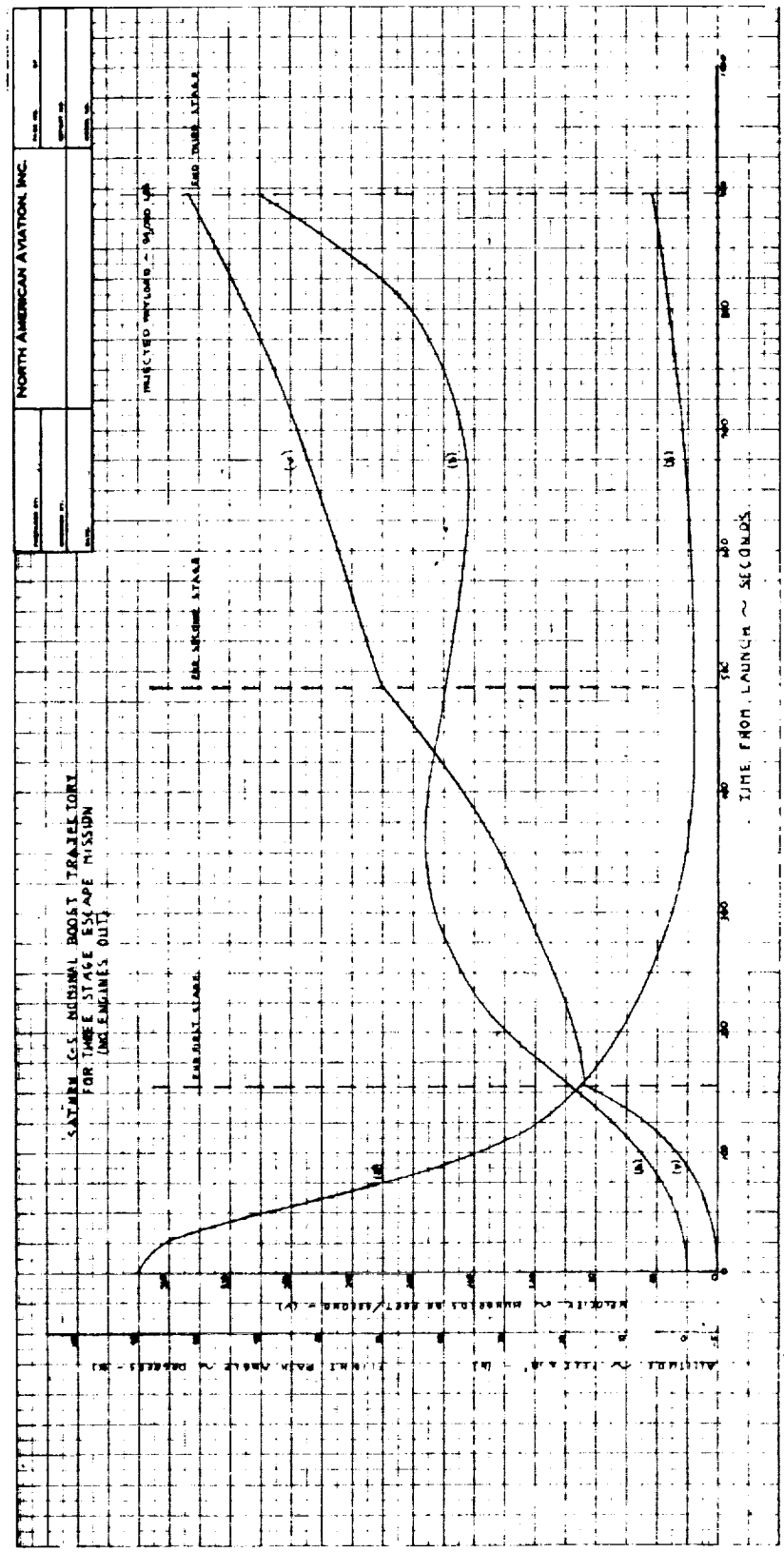

Figure 4. Saturn C-5 Nominal Boost Trajectory for Three-Stage Escape Mission

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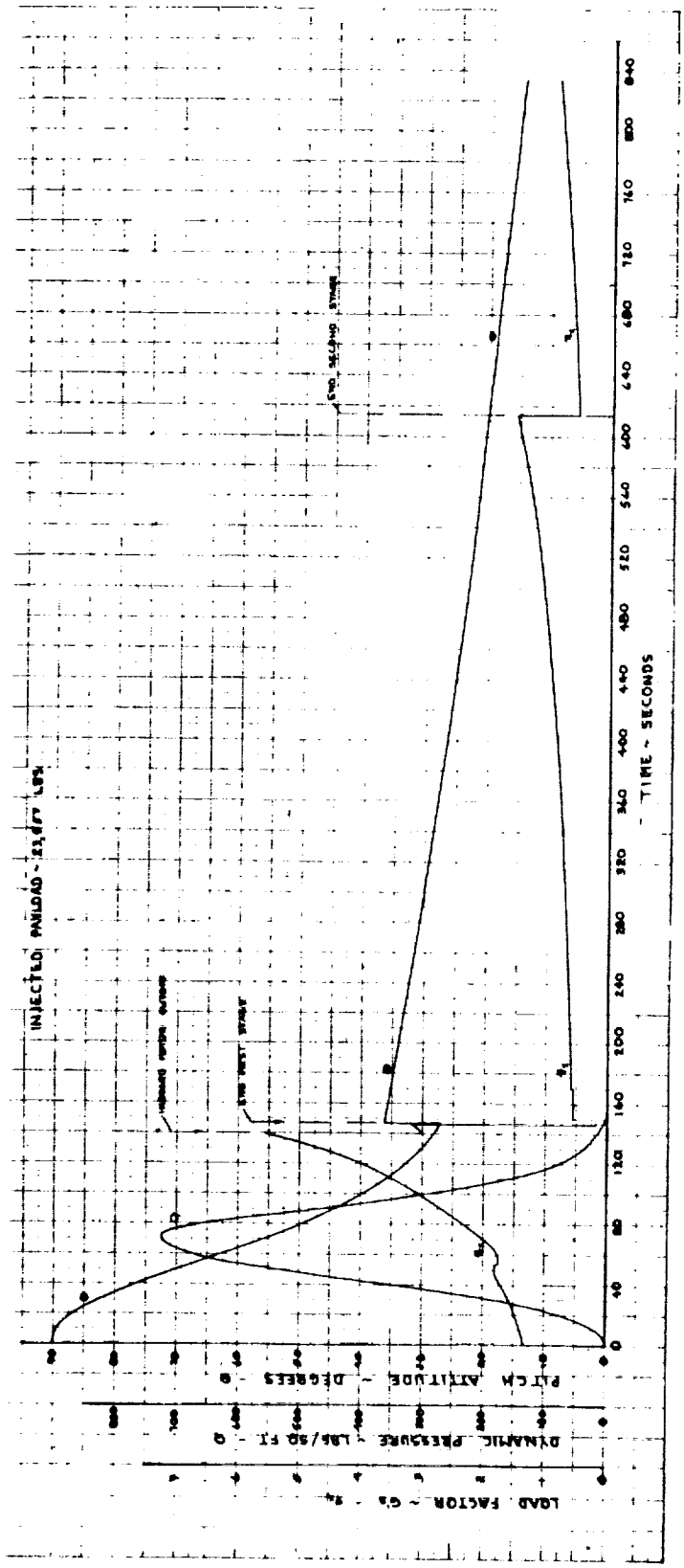

Figure 5. Saturn C-1, 100 Nautical Mile Orbit

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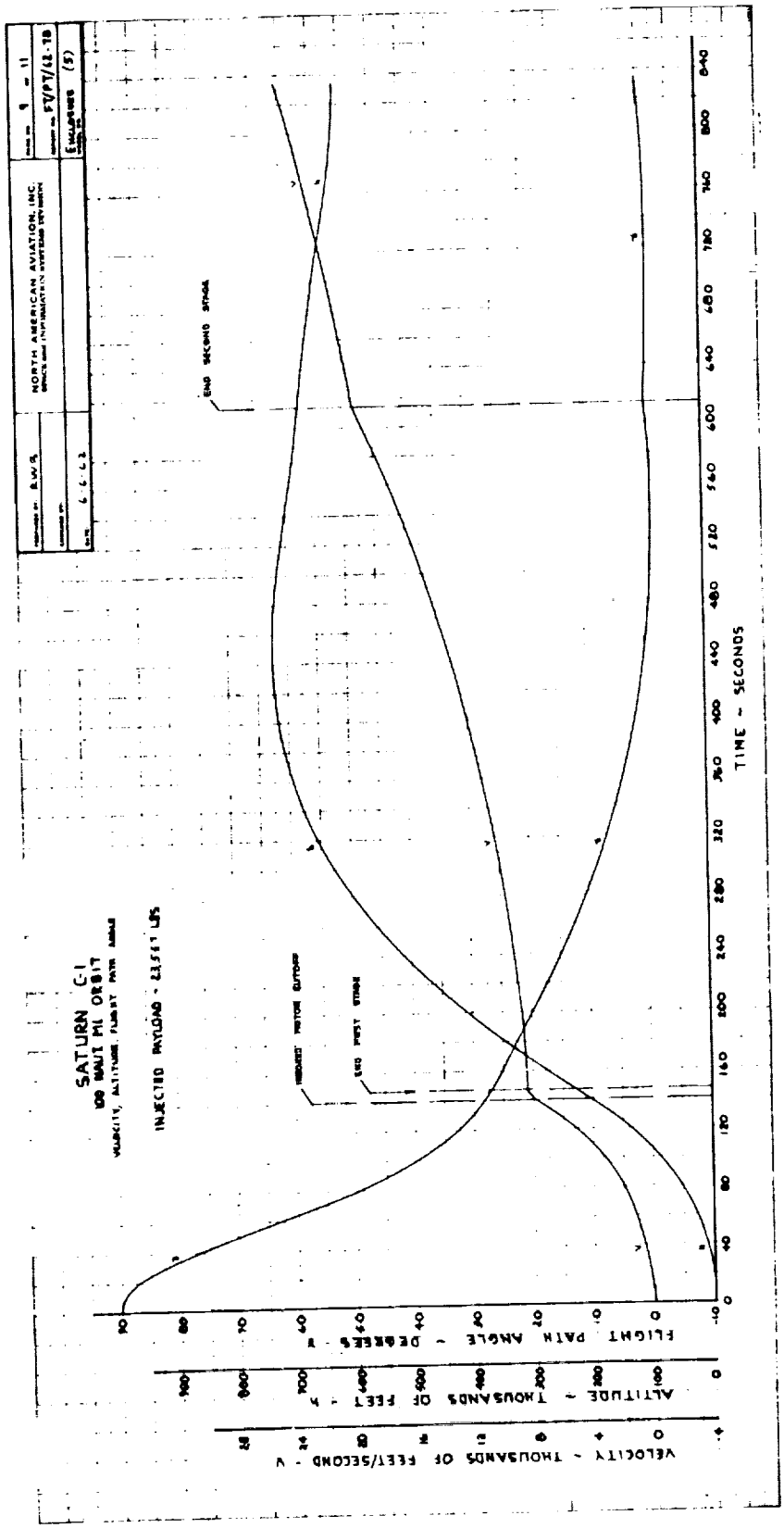

Figure 6. Saturn C-1, 100 Nautical Mile Orbit

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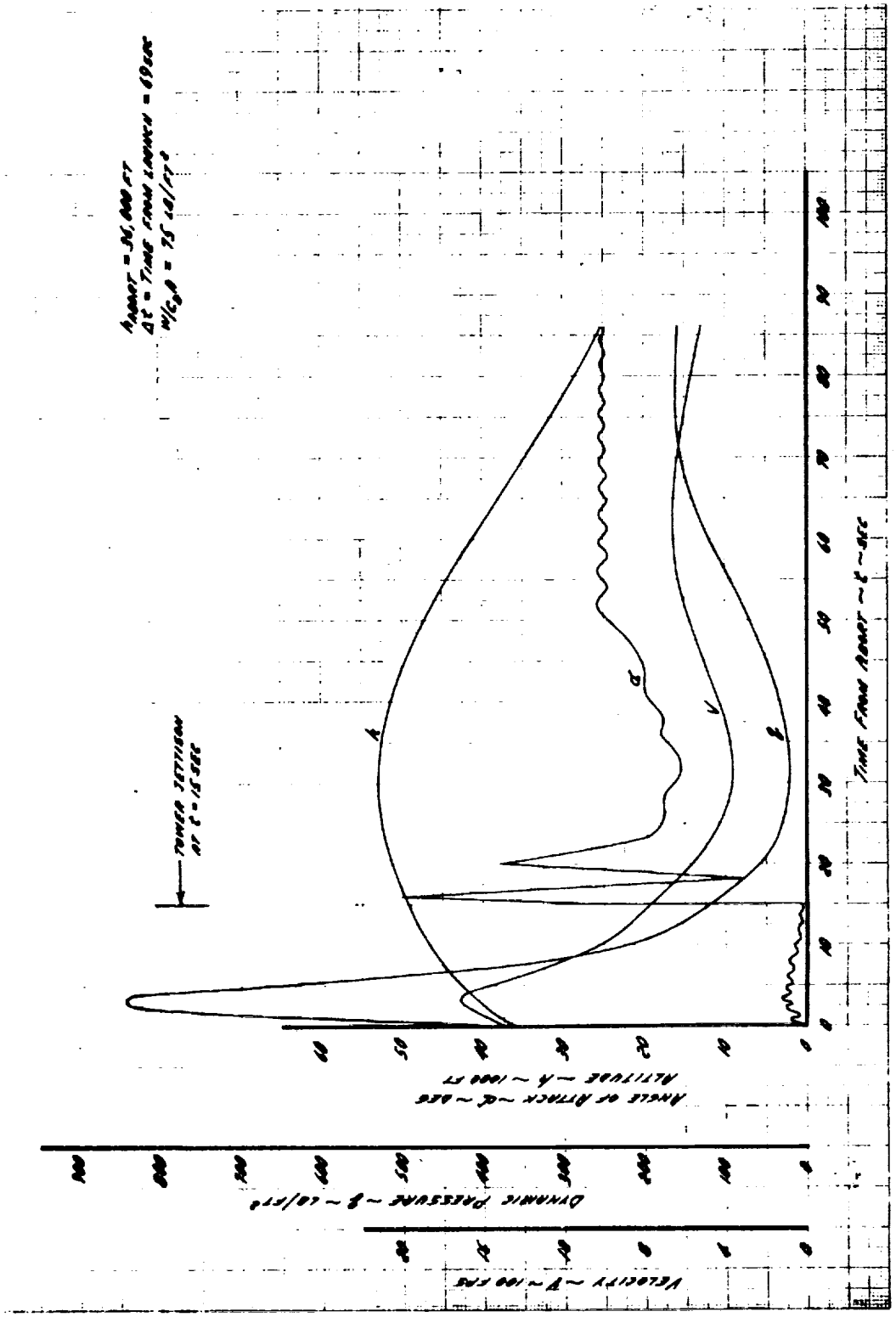

Figure 7. Trajectory No. HSA-1, LES Abort (C-1) Boost, Maximum Dynamic Pressure

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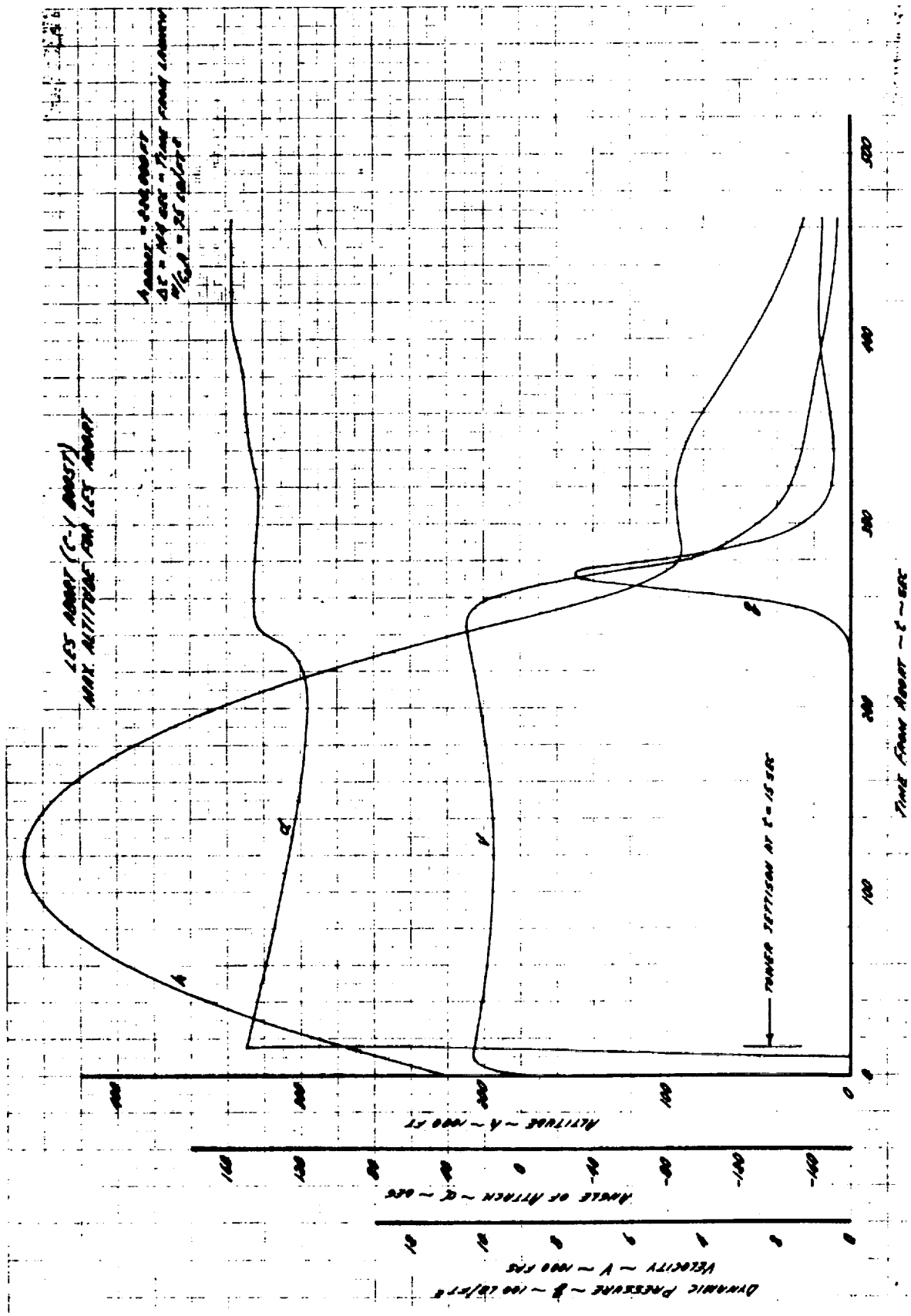

Figure 8. Trajectory No. HSA-3, LES Abort (C-1) Boost Maximum Altitude for LES Abort

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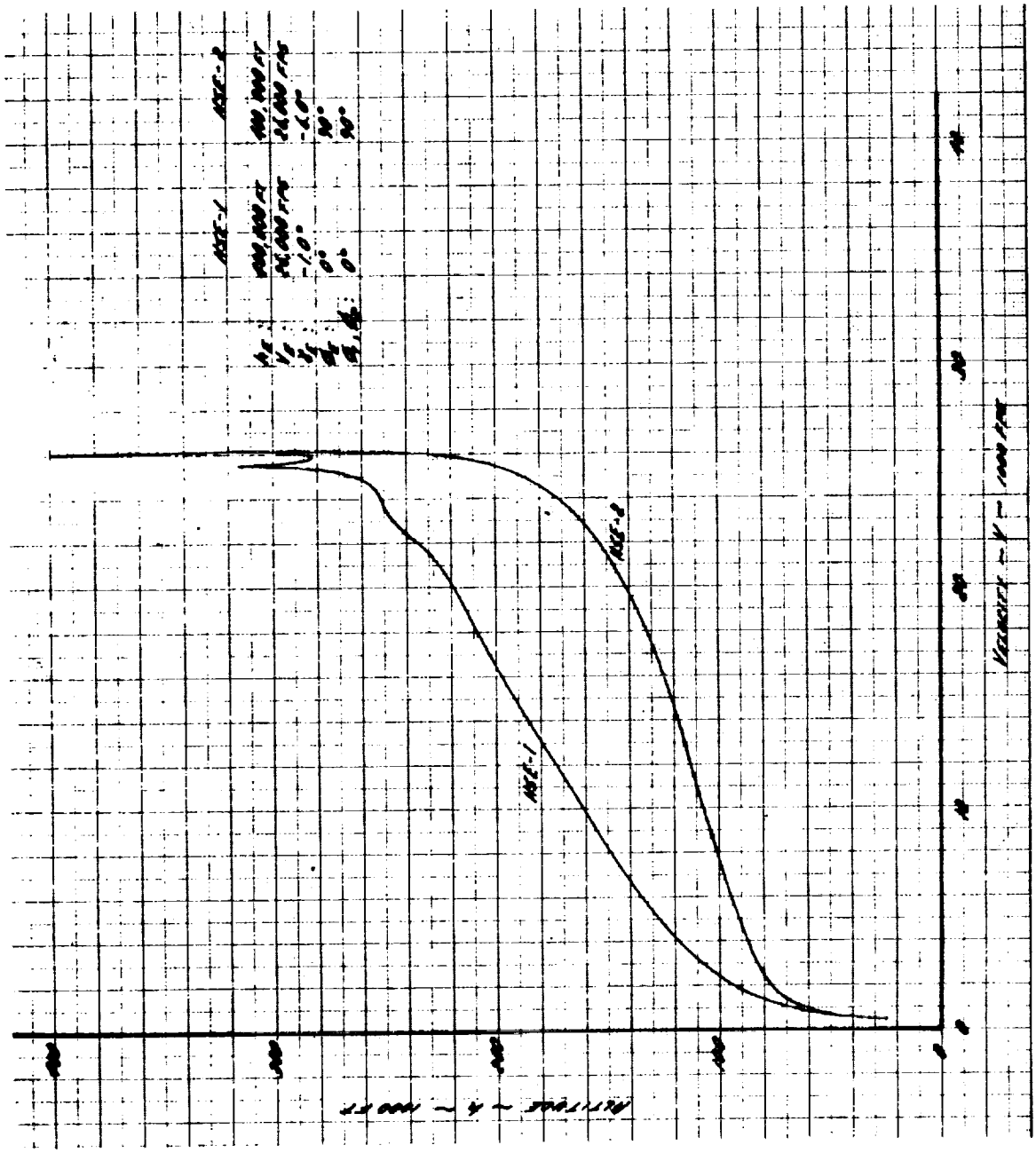

Figure 9. Satellite Speed Entries (h Versus V Profiles)

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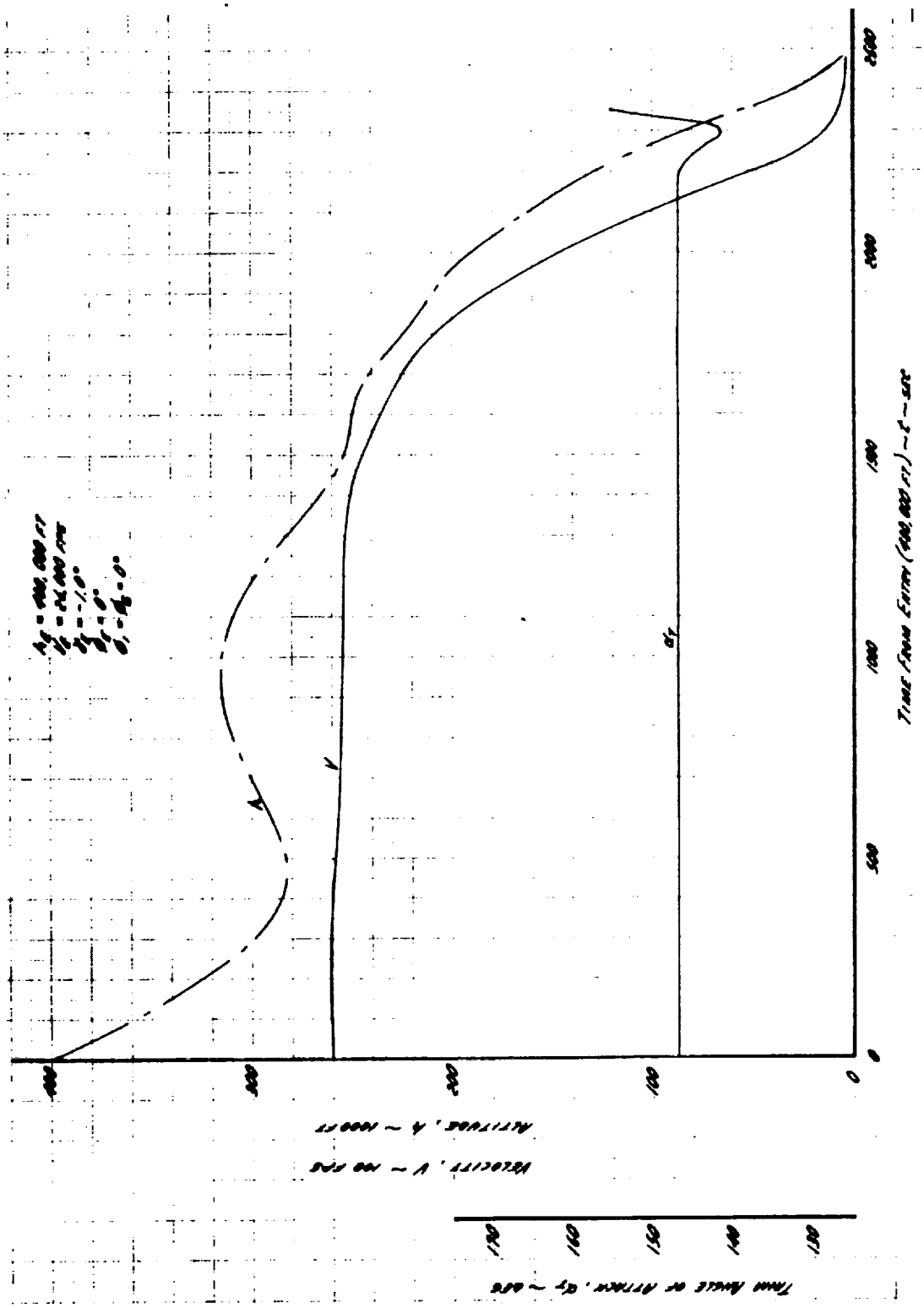

Figure 10. Trajectory No. HSE-1, Satellite Speed Entry, Maximum L/D

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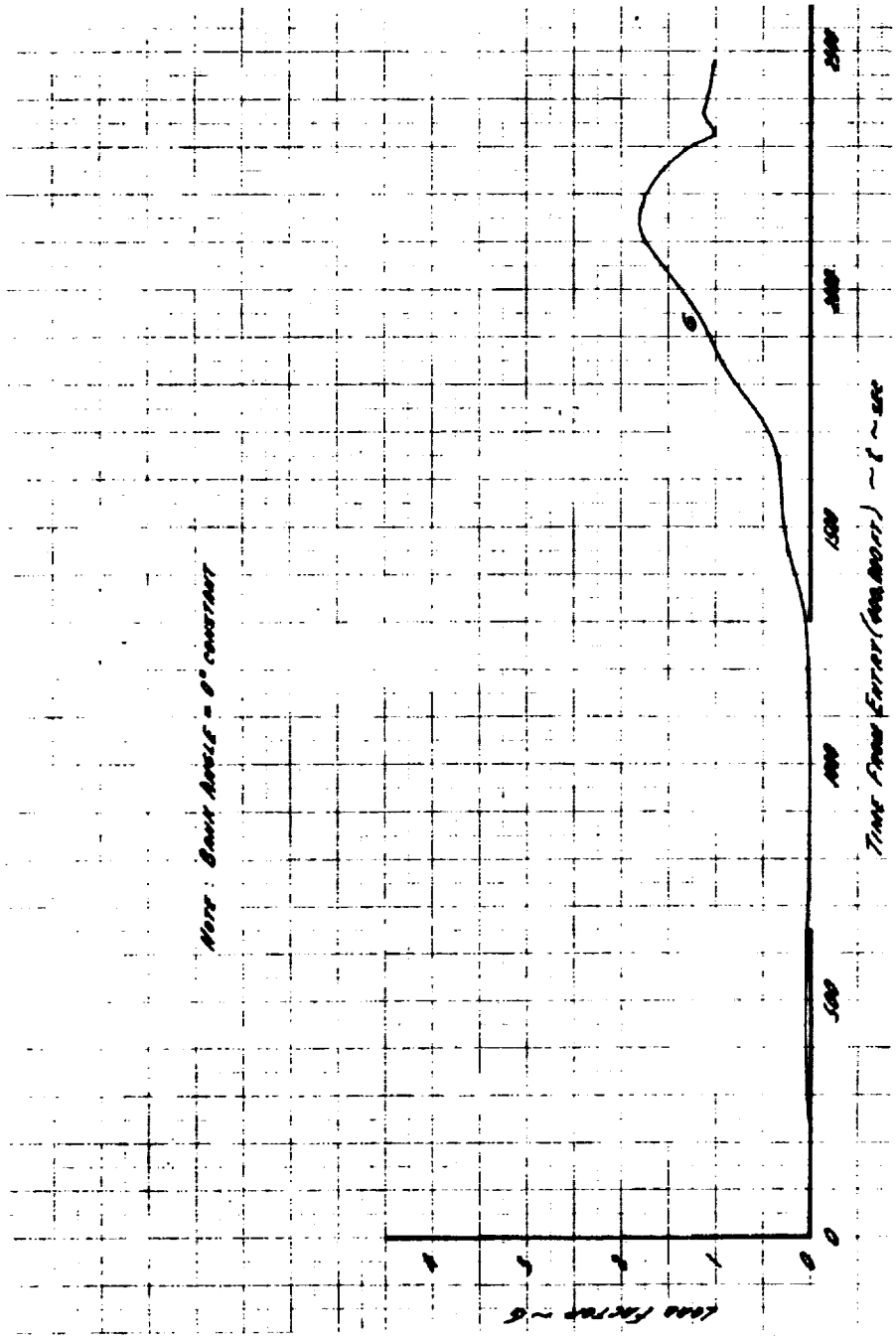

Figure 11. Trajectory No. HSE-1, Satellitic Speed Entry, Maximum L/D

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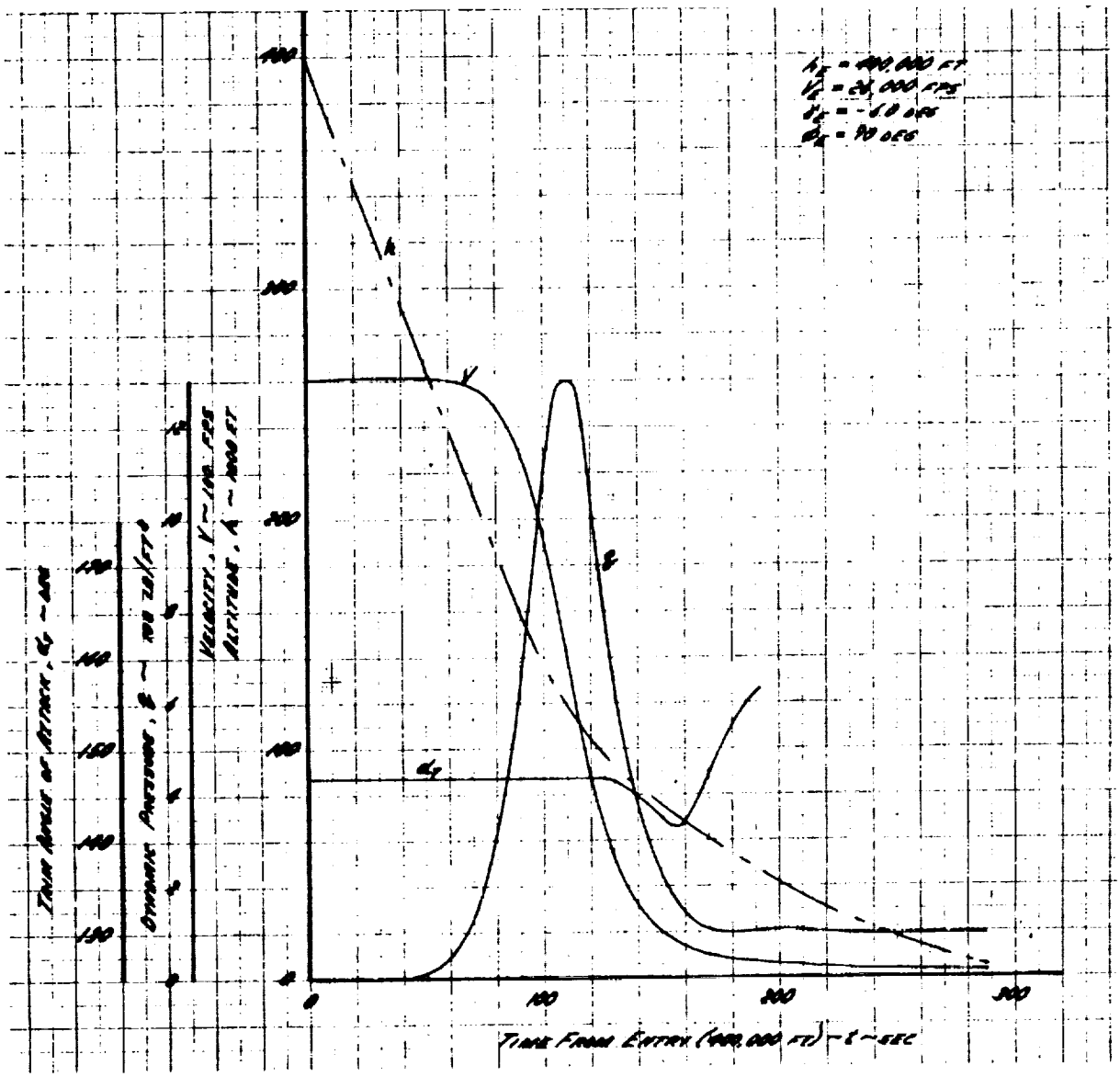

Figure 12. Trajectory No. HSE-2, Satellitic Speed Entry, Maximum 20g

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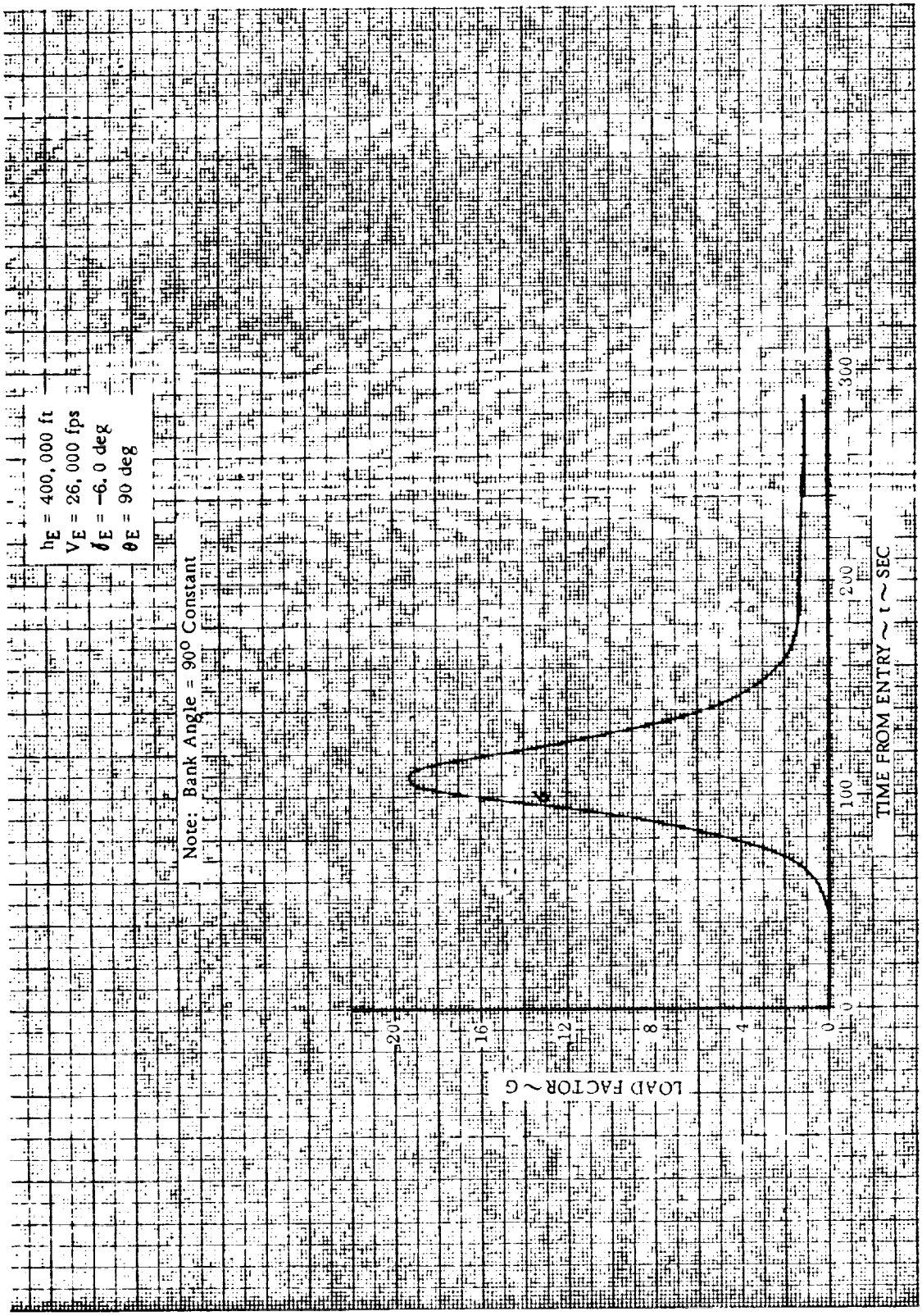

Figure 13. Trajectory No. HSE-2, Satellitic Speed Entry, Maximum 20g

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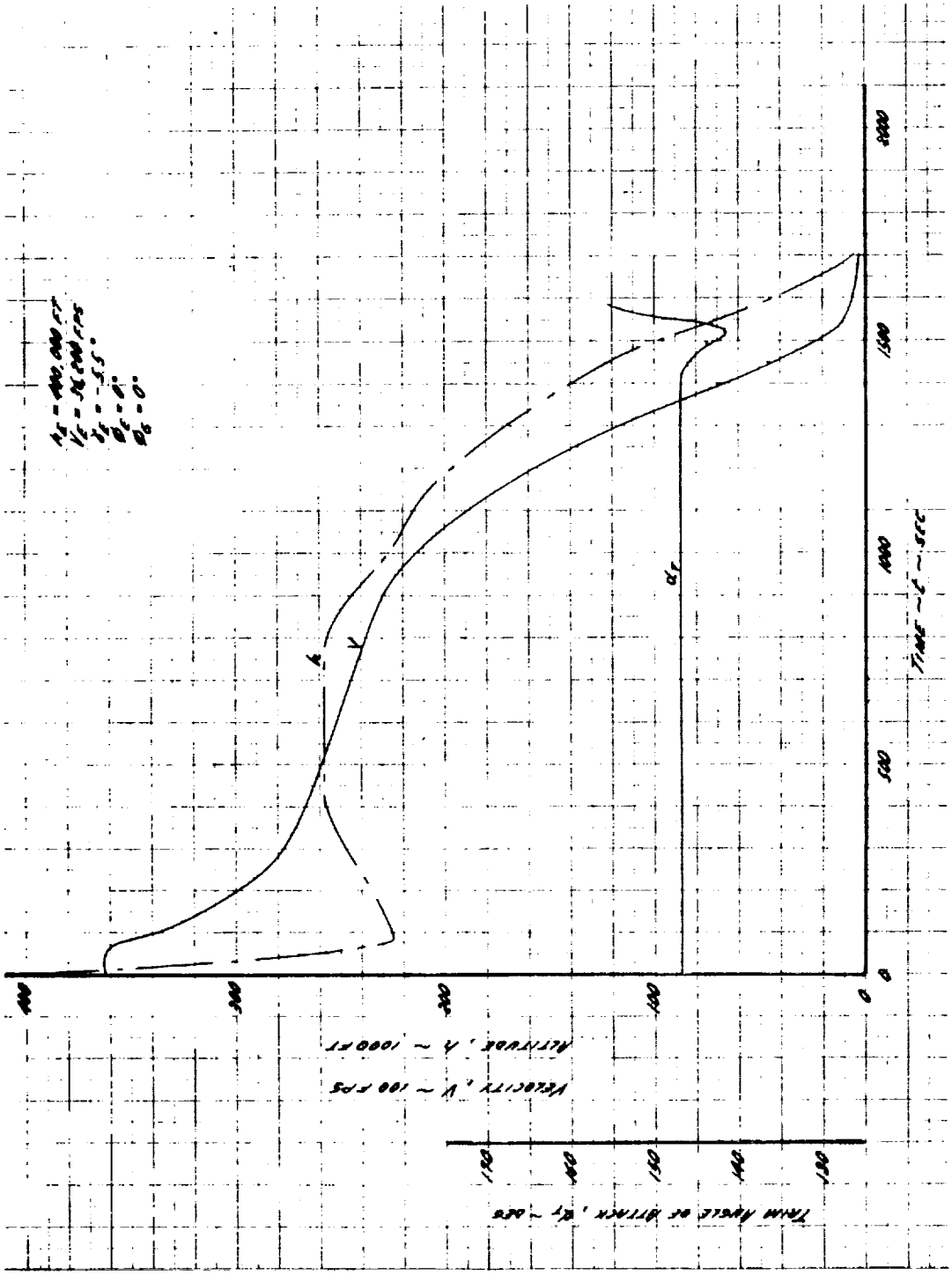

Figure 15. Trajectory No. HSE-3A, Escape Speed Entry, Maximum Q at $\bar{V}>1$, Maximum Q at $\bar{V}<1$

[redacted]

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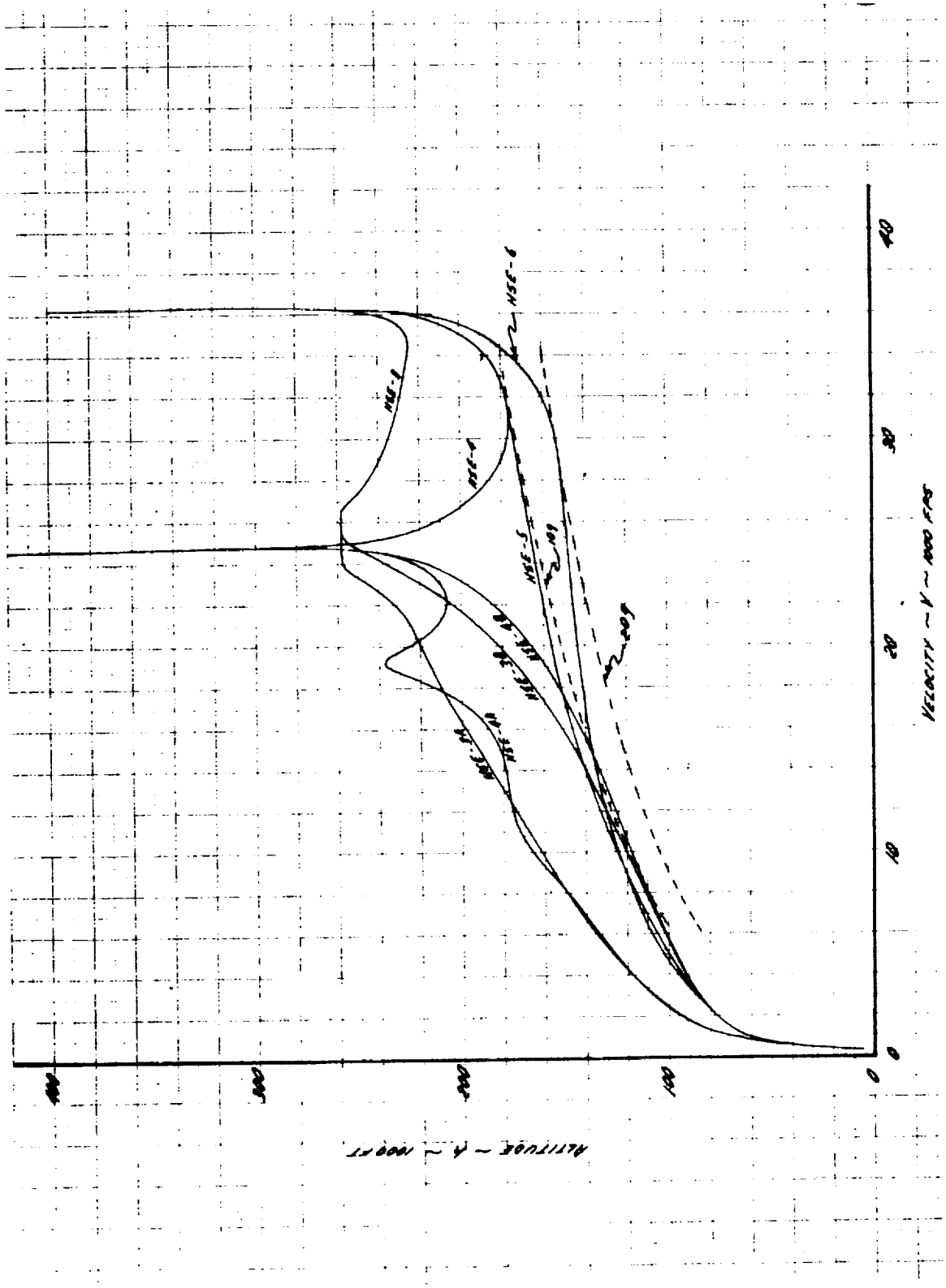

Figure 14. Escape Speed Entry, h Versus V Profile

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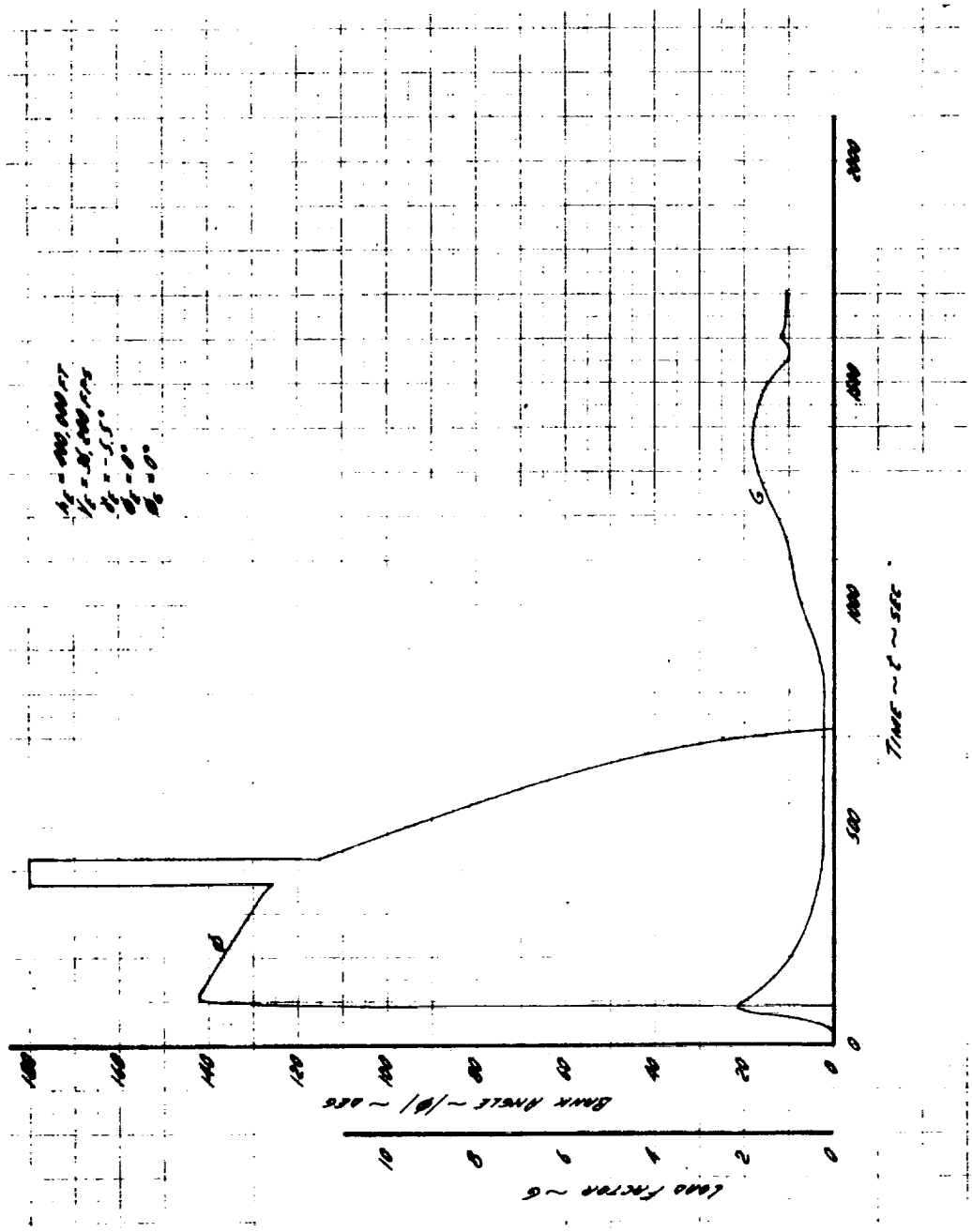

Figure 16. Trajectory No. HSE-3A, Escape Speed Entry, Maximum Q at $\bar{V}>1$, Maximum Q at $\bar{V}<1$

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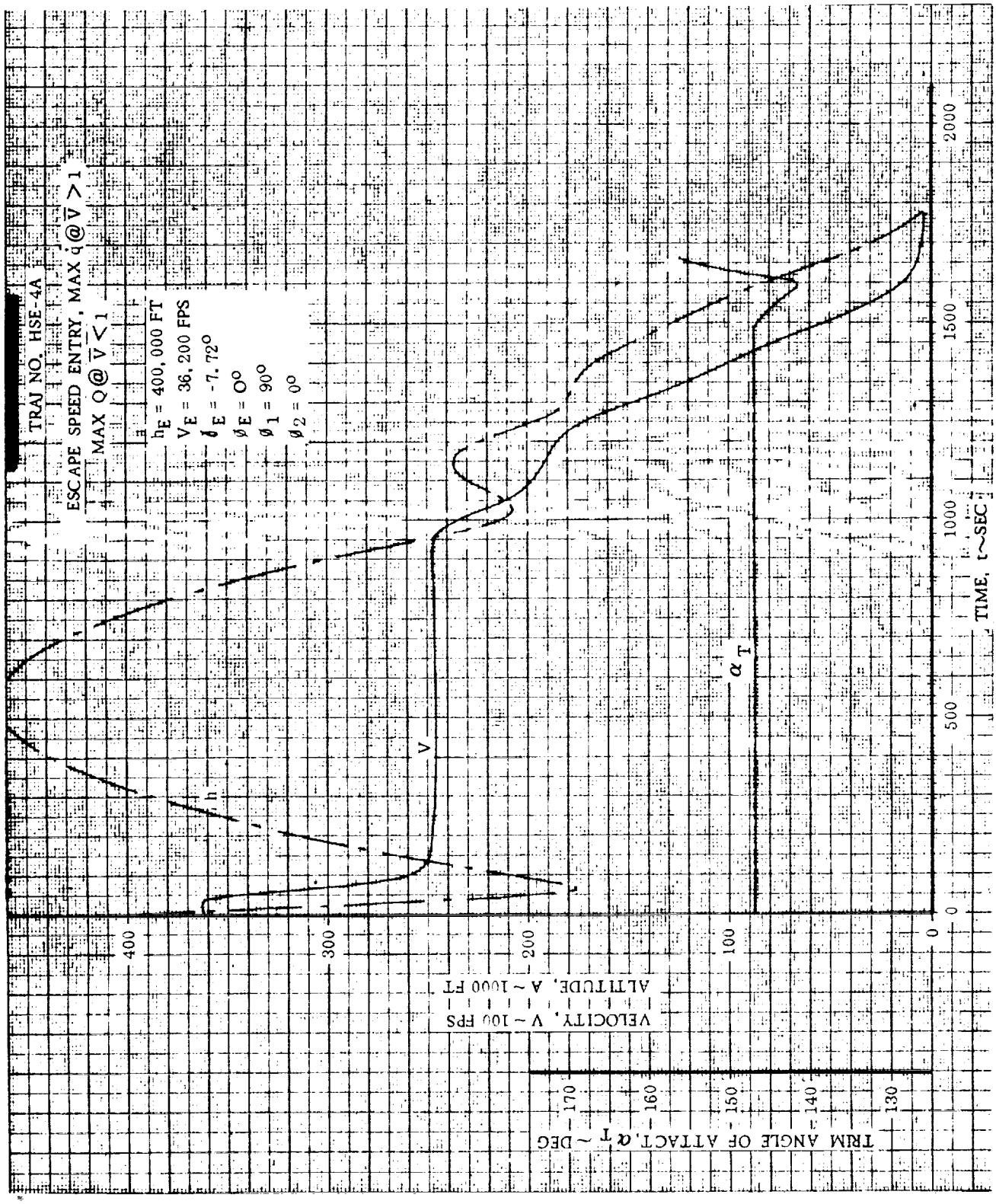

Figure 17. Trajectory No. HSE-4A, Speed Entry, Maximum q at $\overline{V} > 1$, Maximum Q at $\overline{V} < 1$

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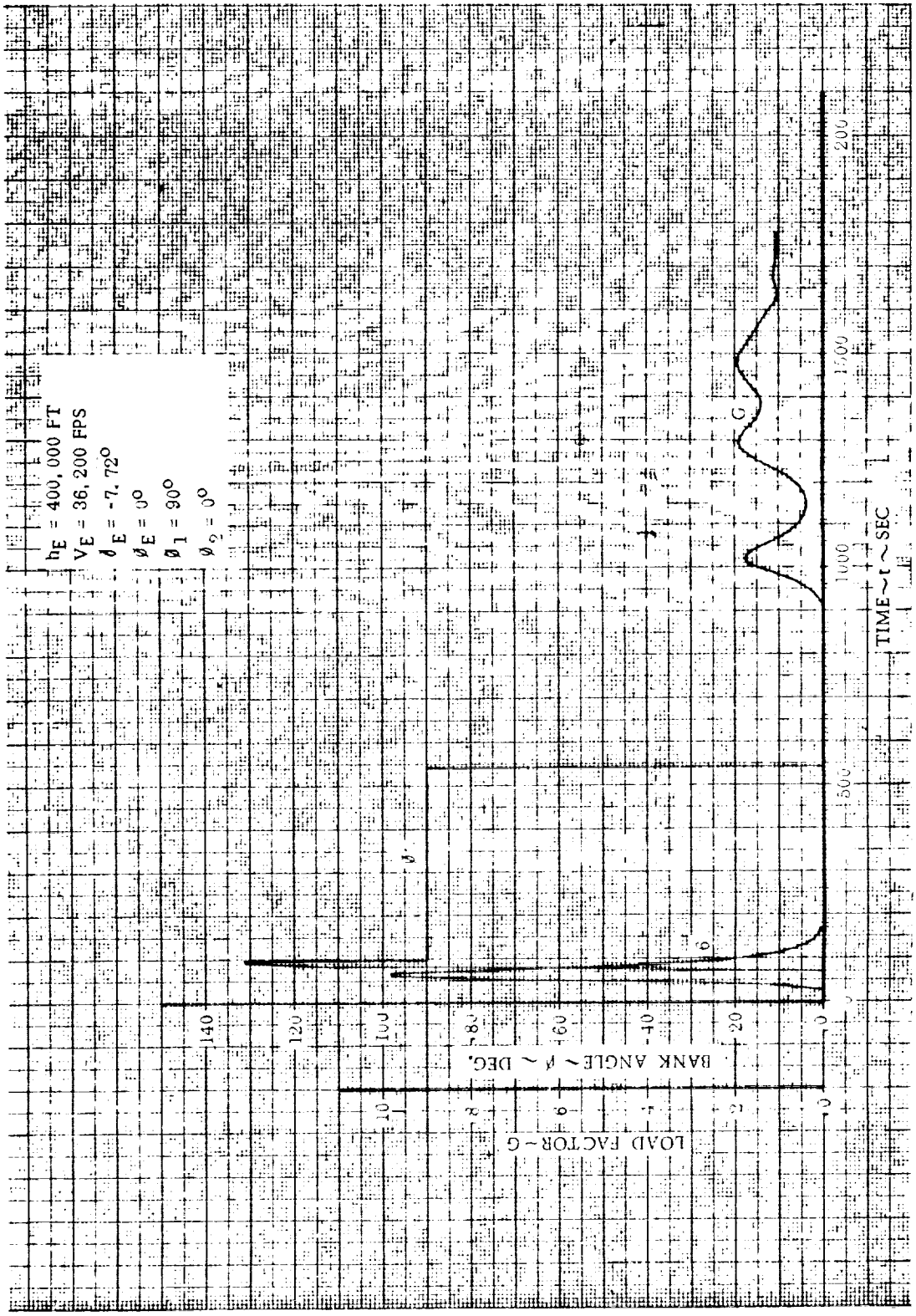

Figure 18. Trajectory No. HSE-4A, Speed Entry, Maximum q at $\overline{V} > 1$, Maximum Q at $\overline{V} < 1$

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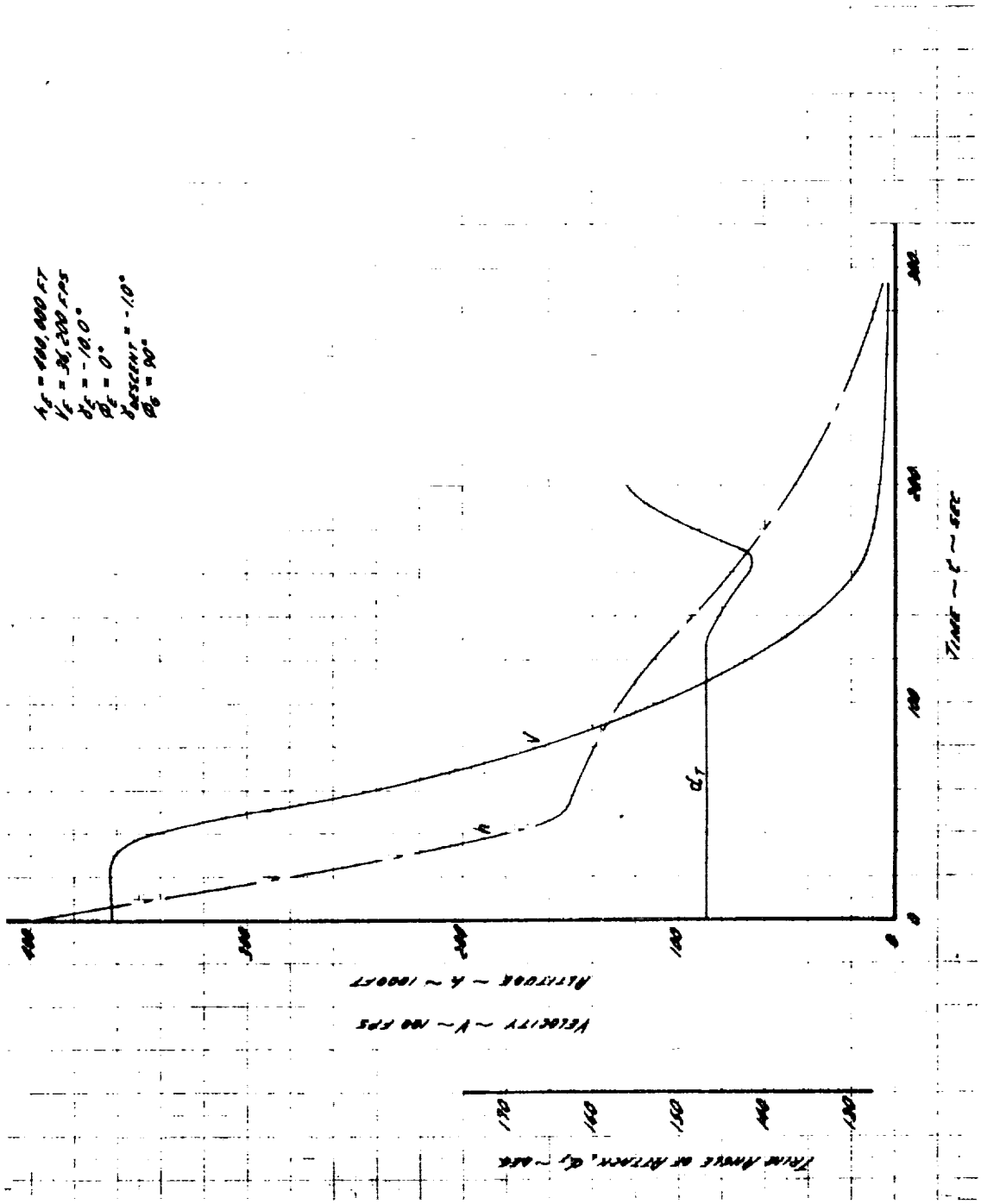

Figure 19. Trajectory No. HSE-6, Escape Speed Entry, Structural Limit Entry

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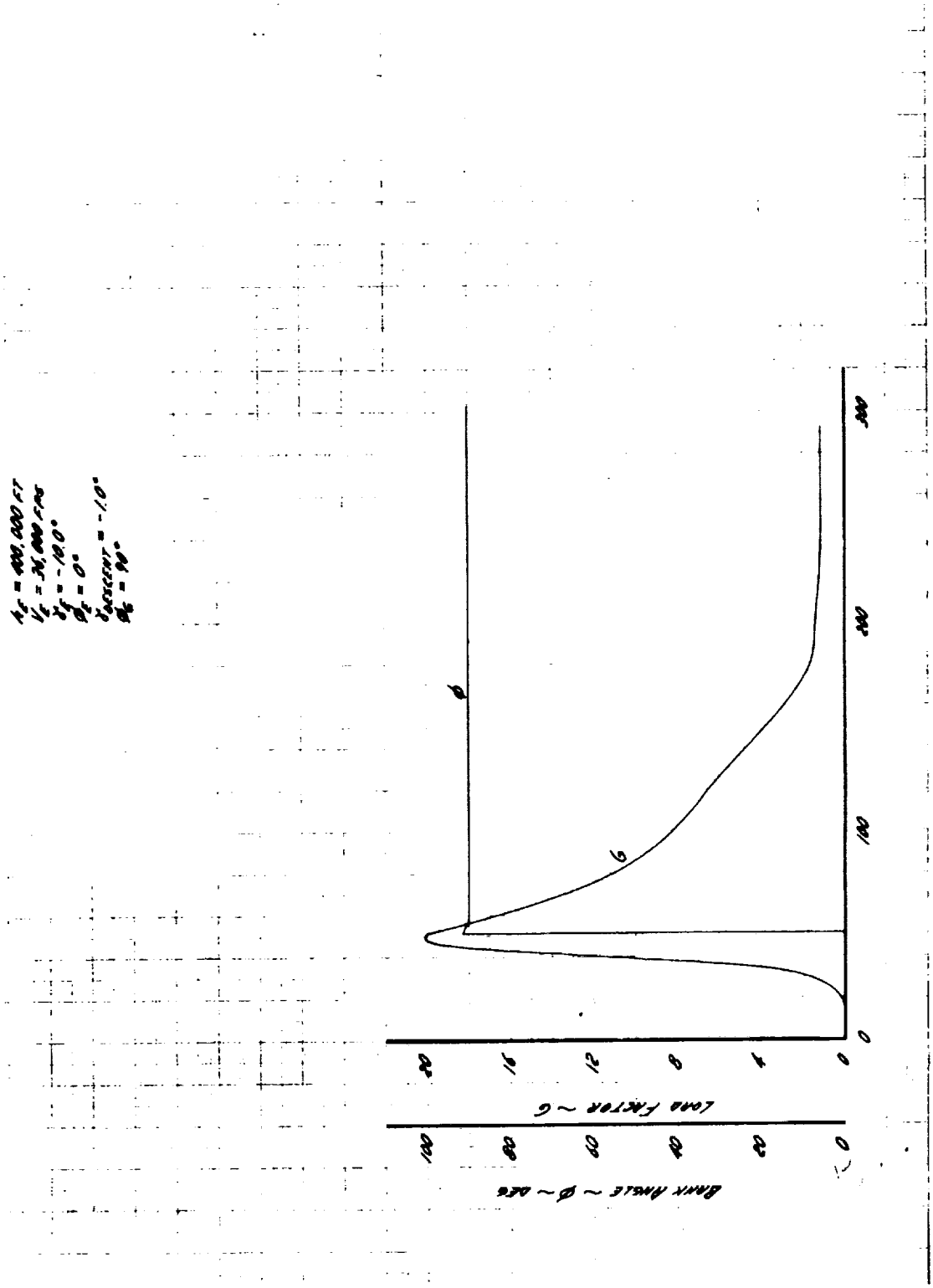

Figure 20. Trajectory No. HSE-6, Escape Speed Entry, Structural Limit Entry

[redacted]

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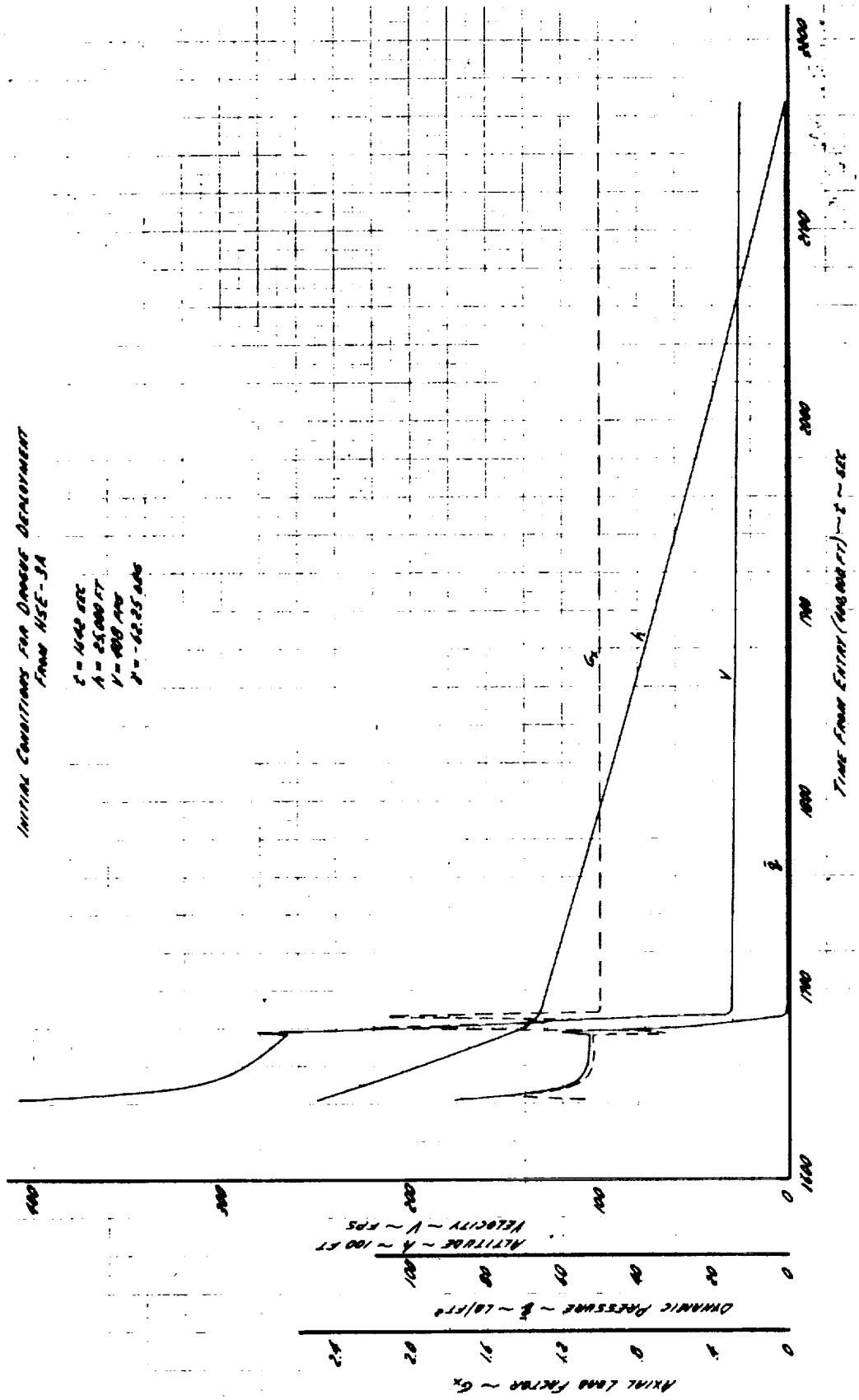

Figure 21. Trajectory No. HSR-1 (3A), Recovery, Maximum Descent Time

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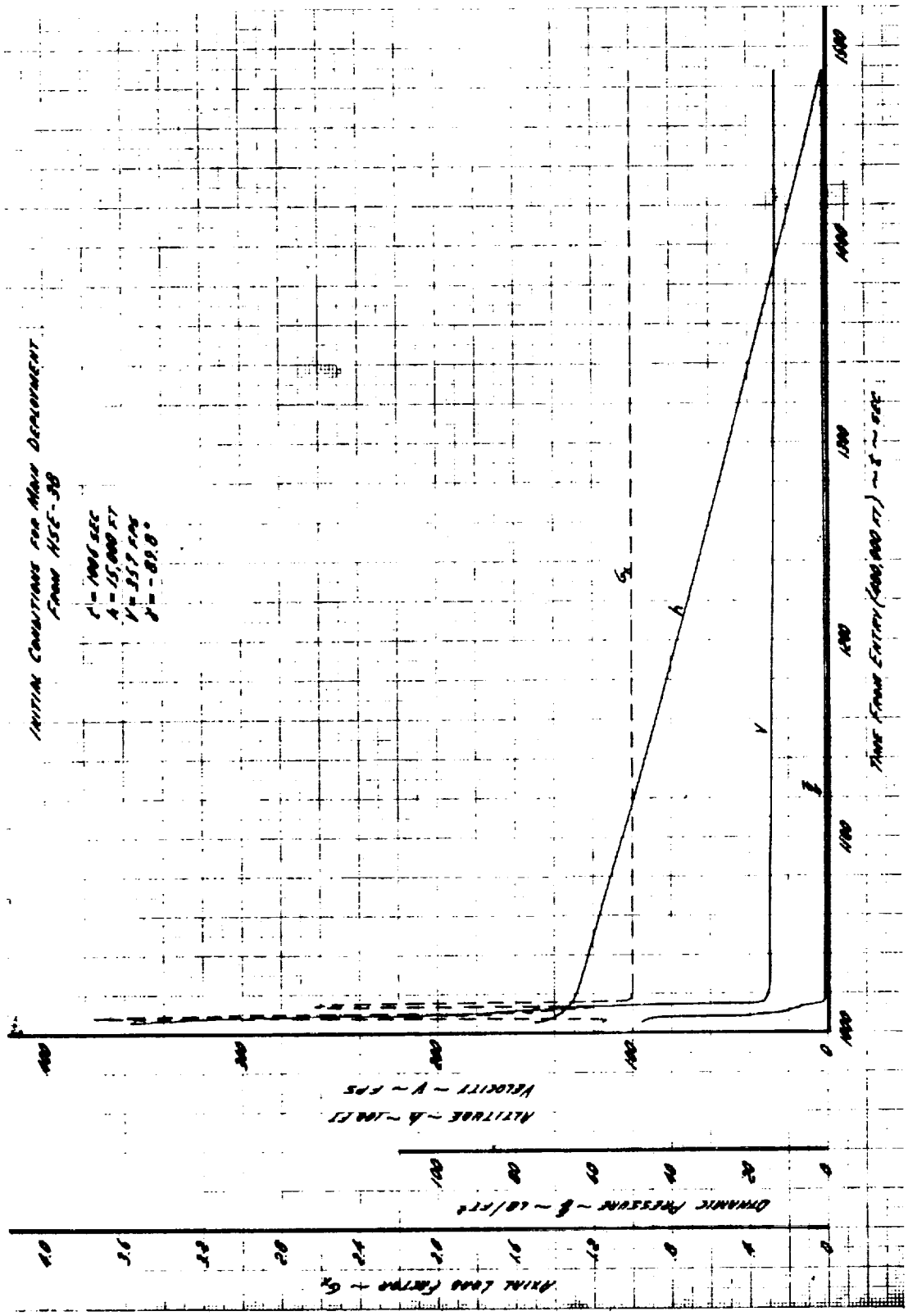

Figure 22. Trajectory No. HSR-2 (3B), Recovery, Minimum Descent Time

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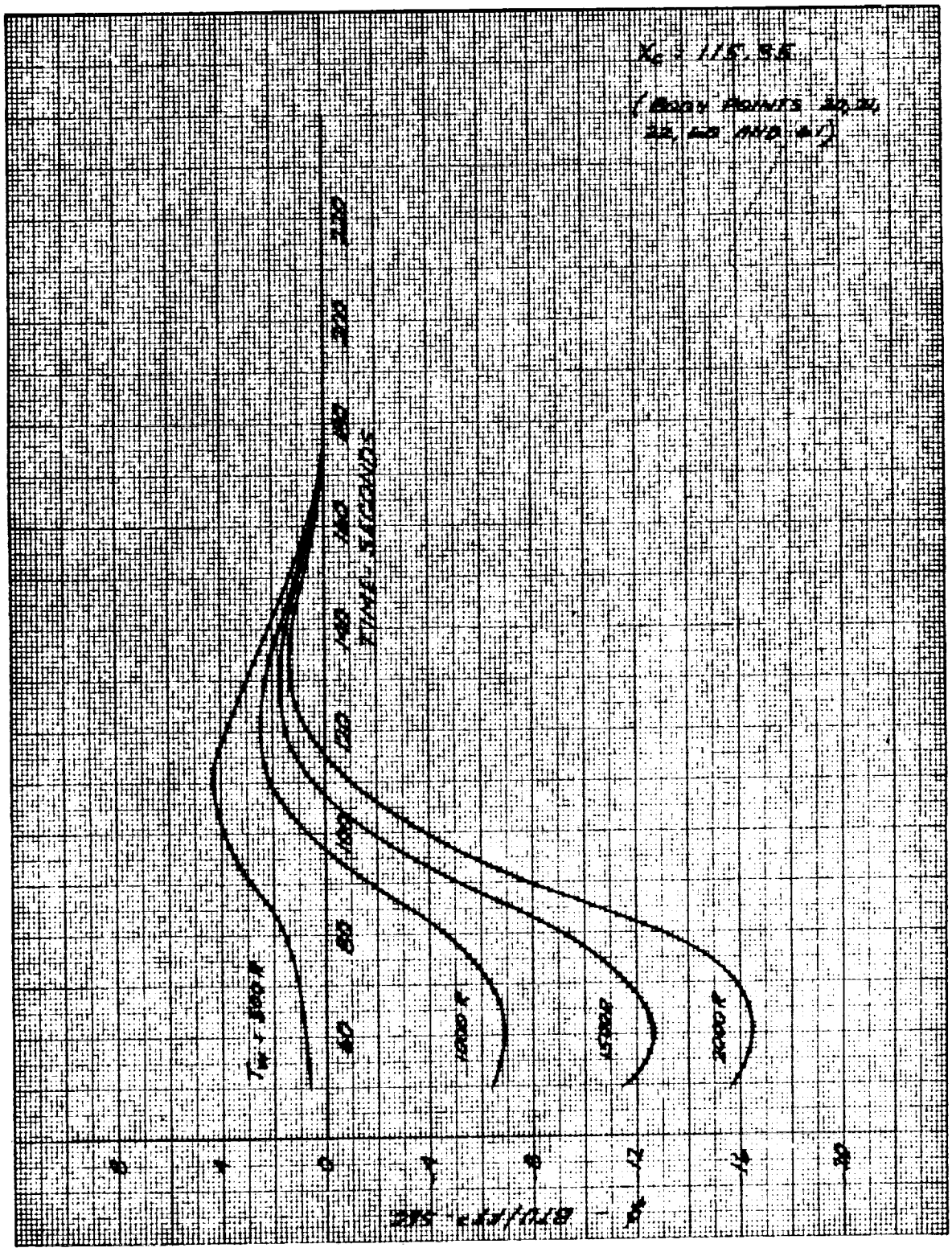

Figure 23. Saturn I Boost Heating, X_c = 115.35

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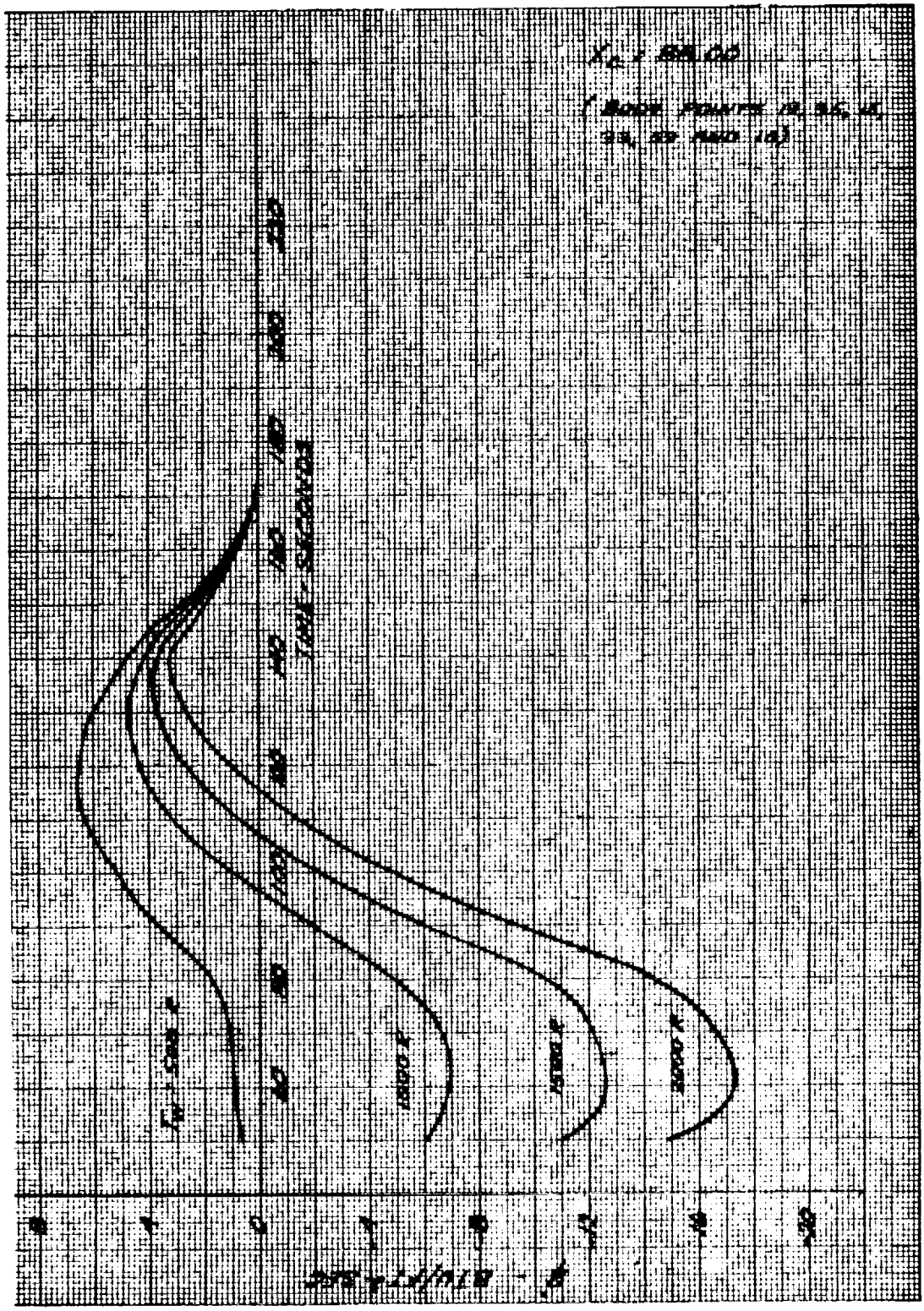

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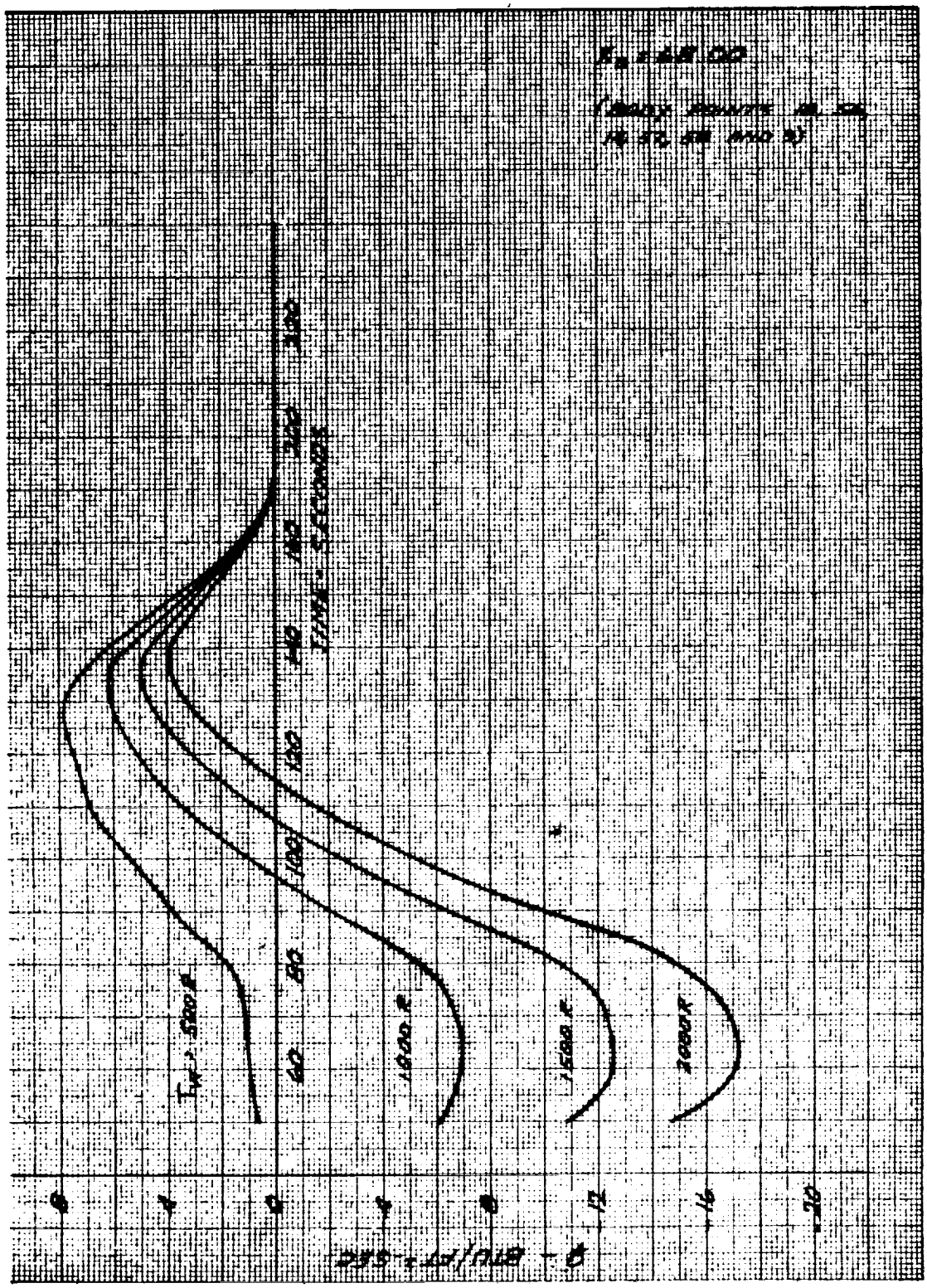

Figure 25. Saturn I Boost Heating, X_c = 68.00

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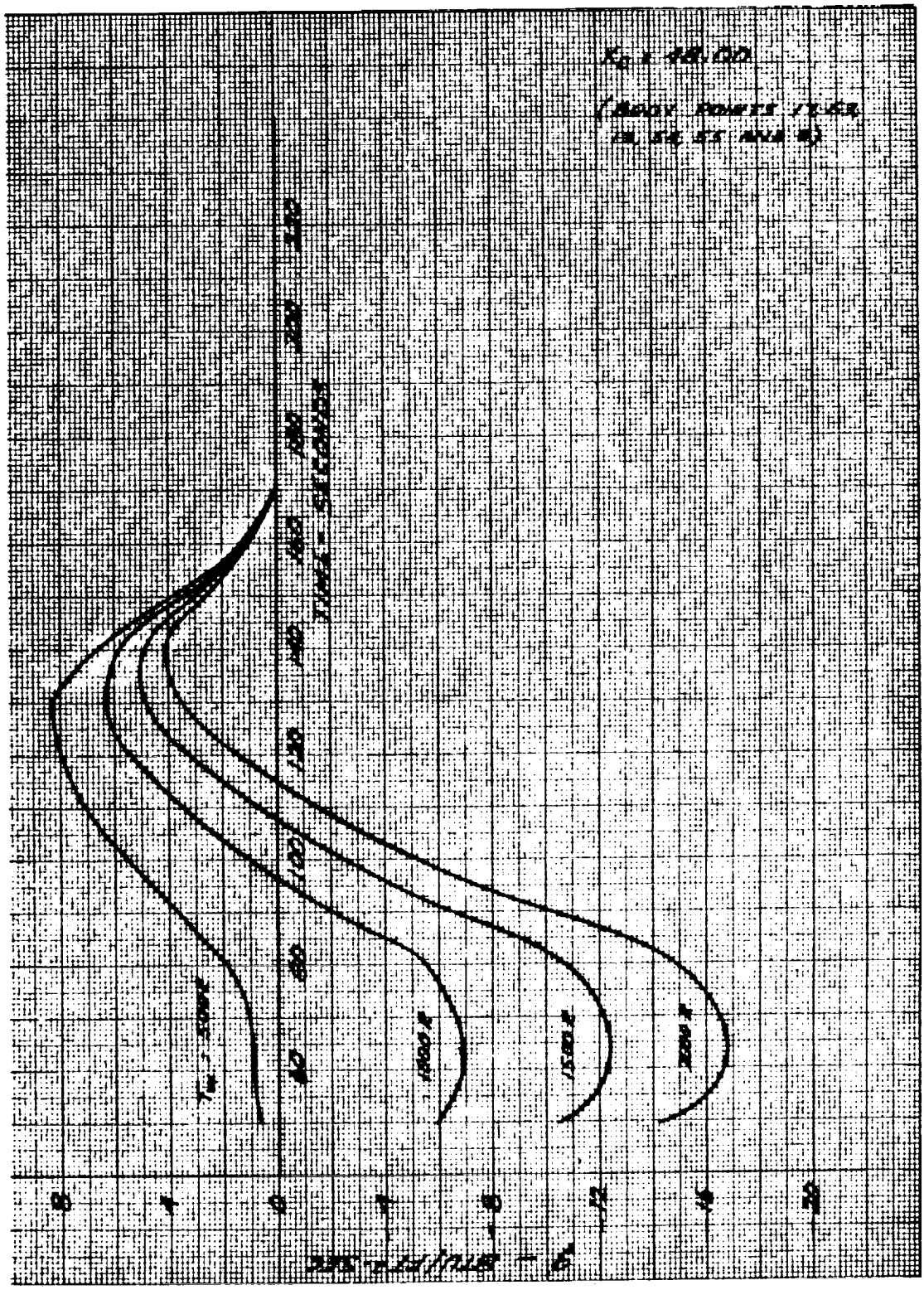

Figure 26. Saturn I Boost Heating, X_c = 48.00

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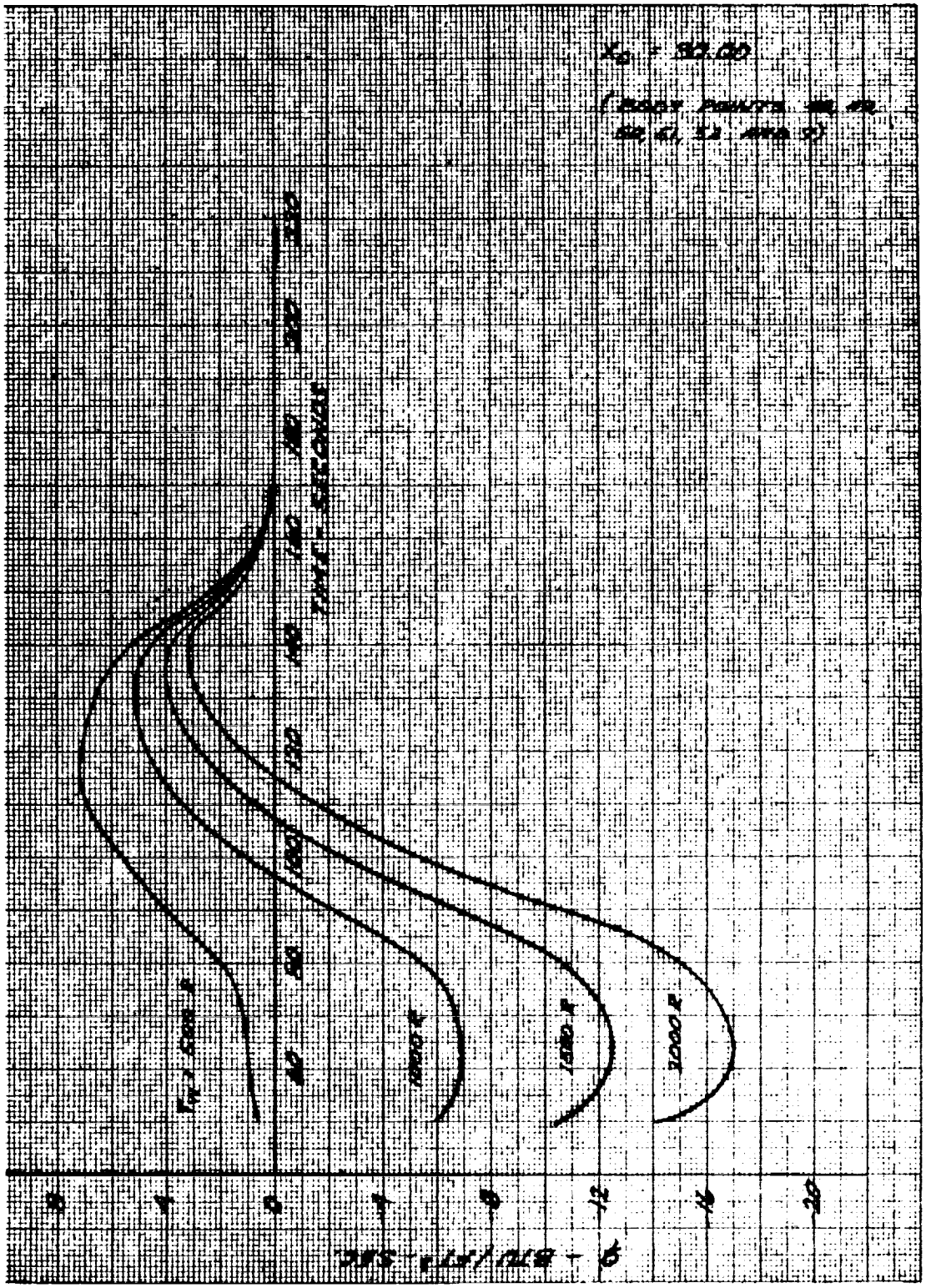

Figure 27. Saturn I Boost Heating, X_c = 30.00

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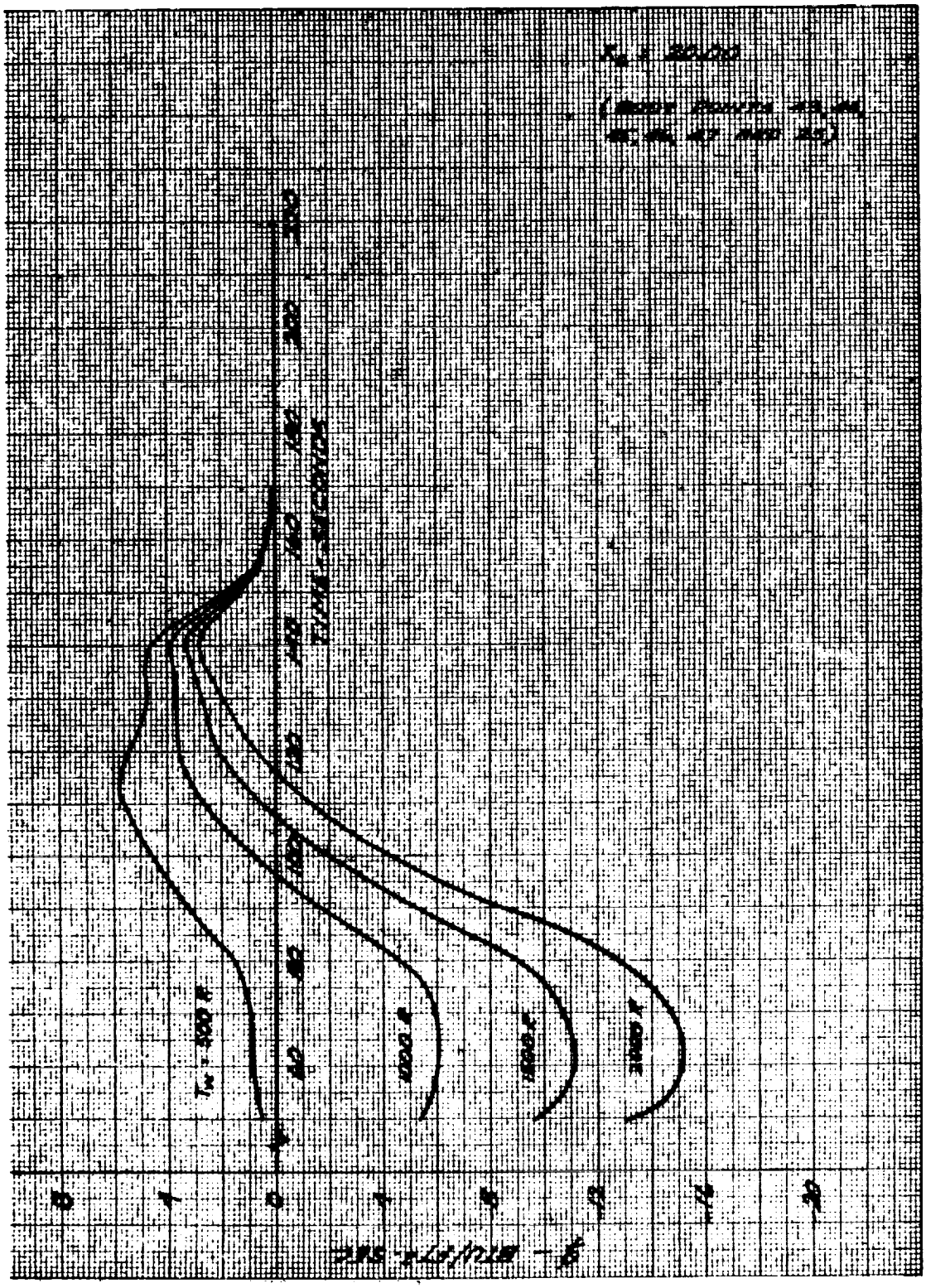

Figure 28. Saturn I Boost Heating, X_c = 20.00

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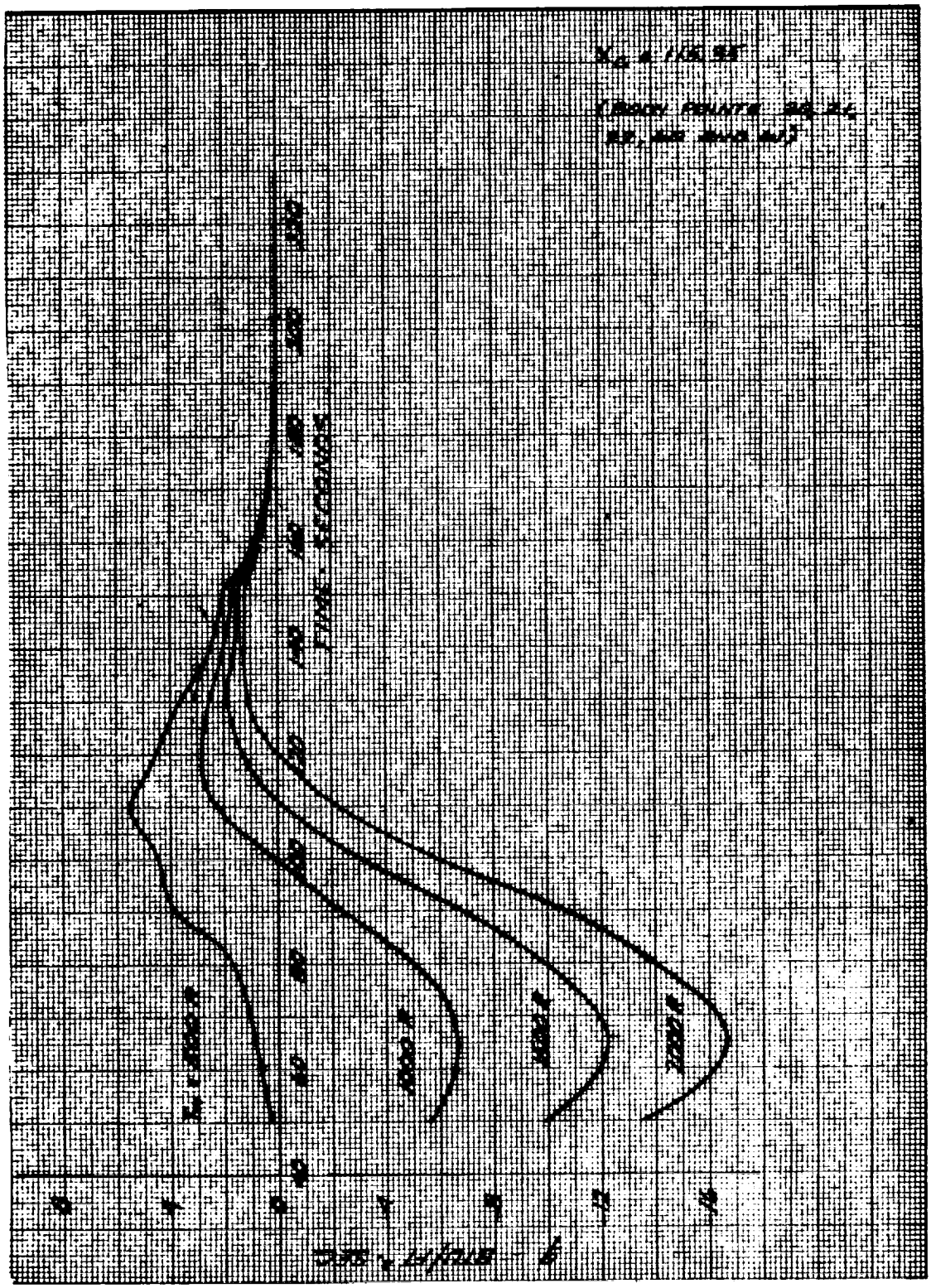

Figure 29. Saturn V Boost Heating, X_c = 115.35

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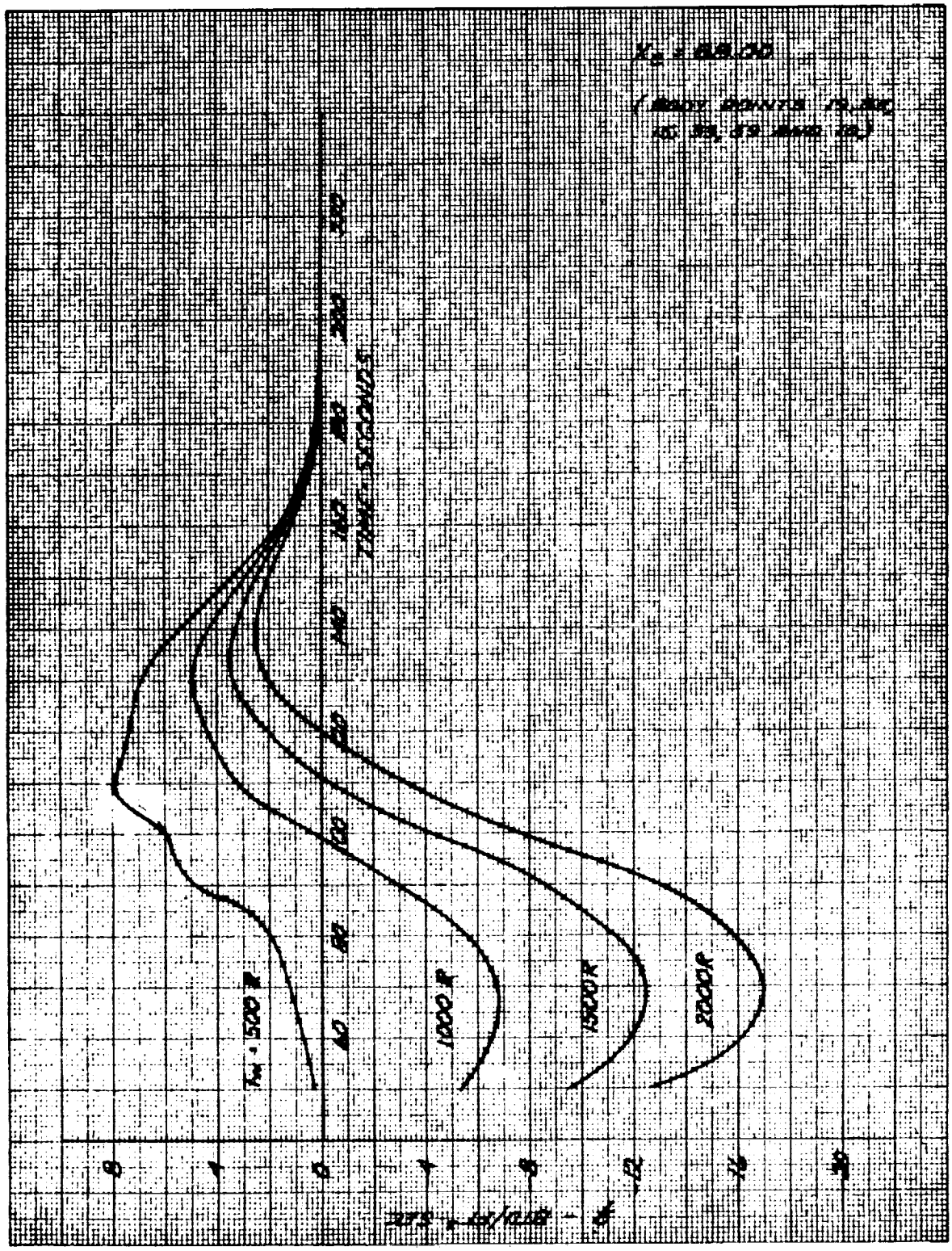

Figure 30. Saturn V Boost Heating, X_c = 88.00

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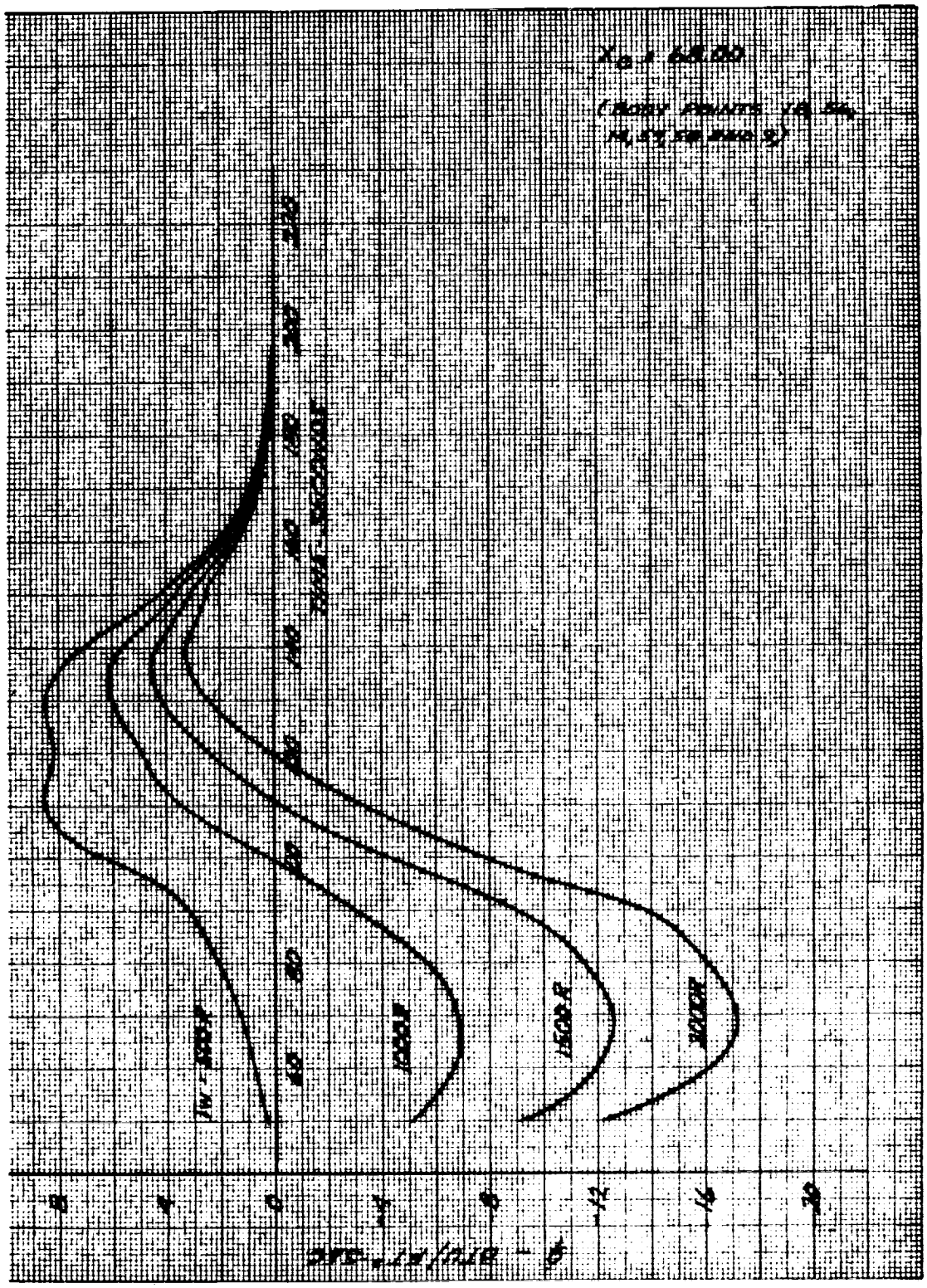

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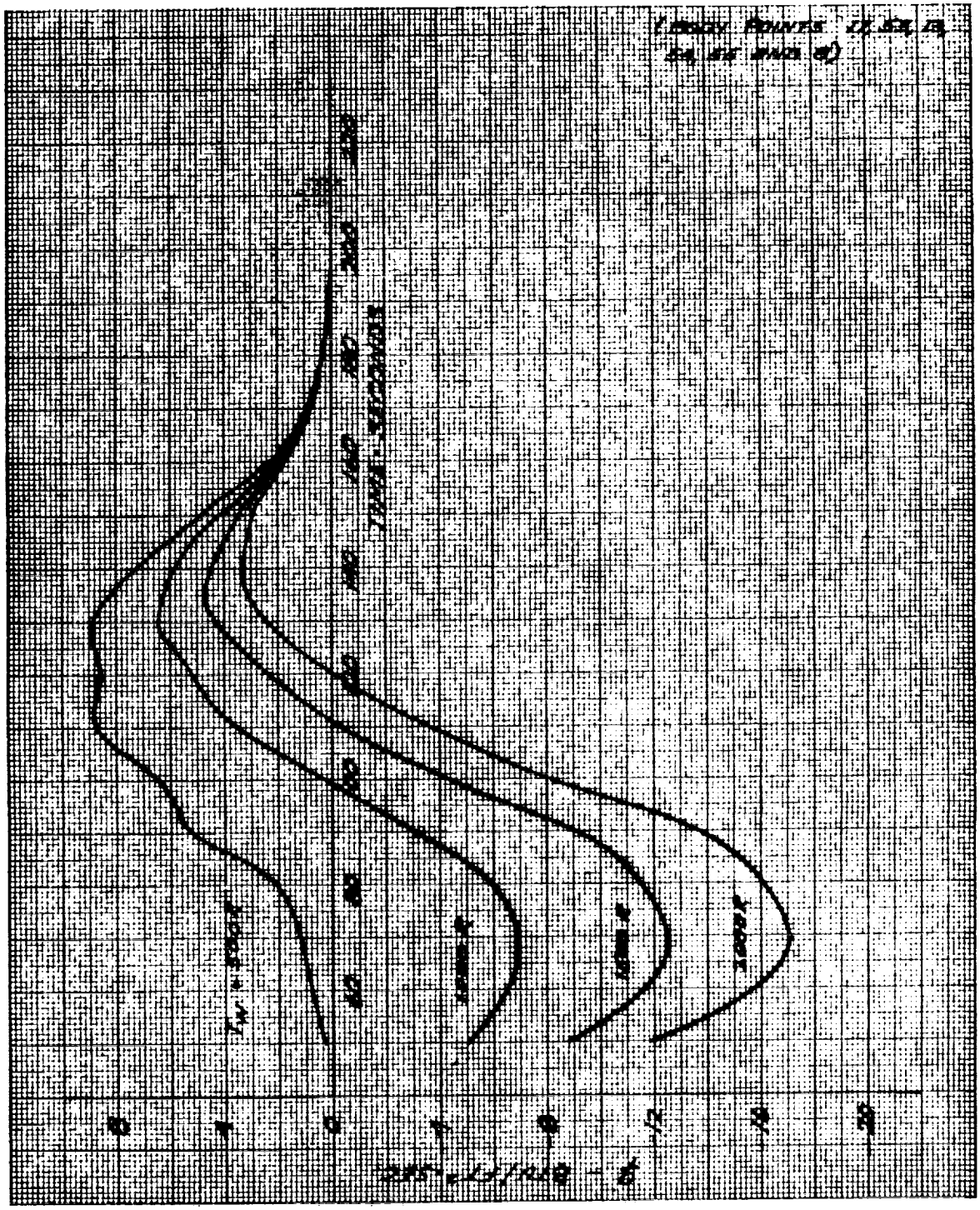

Figure 32. Saturn V Boost Heating, X_c = 48.00

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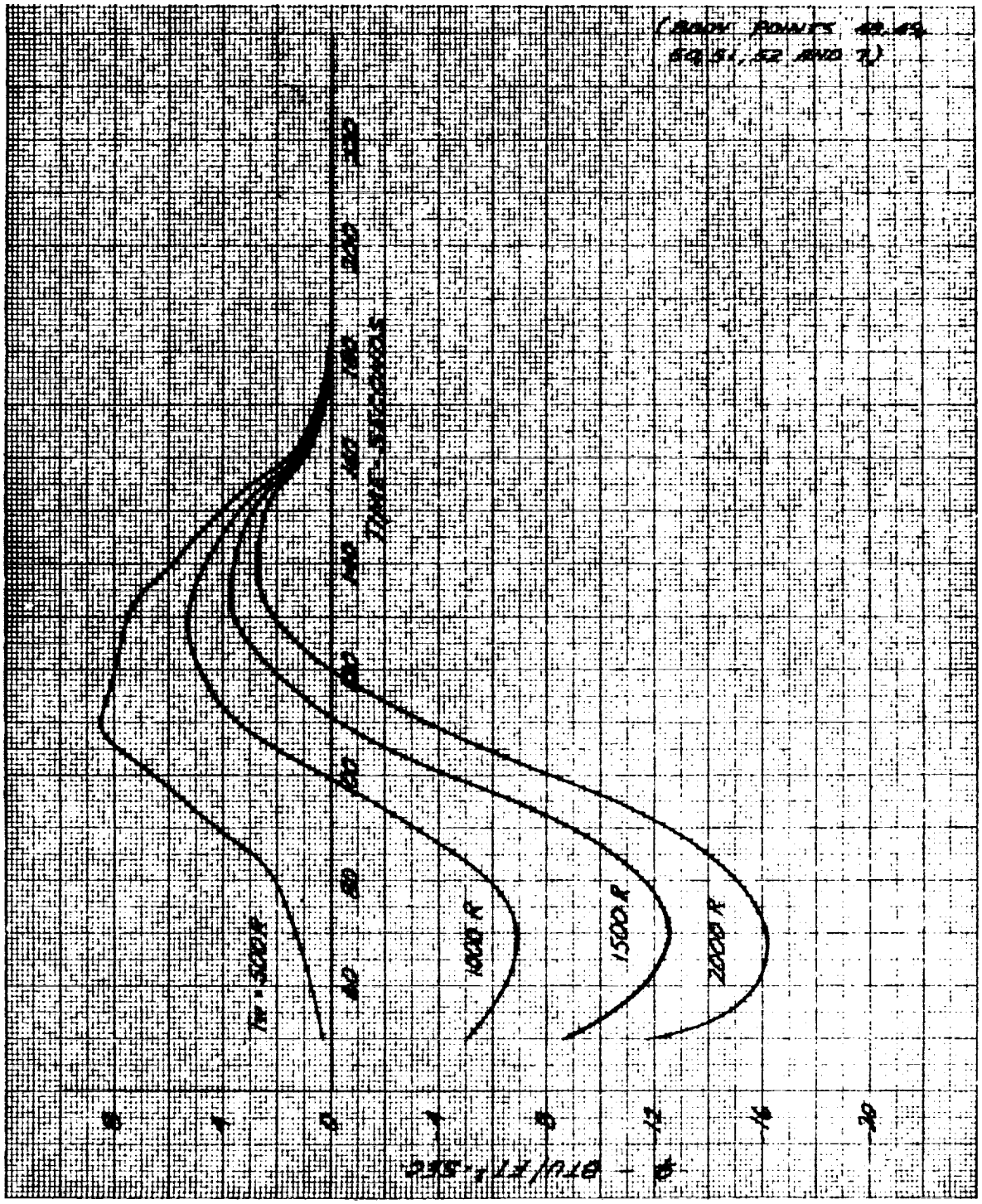

Figure 33. Saturn V Boost Heating, X_c = 30.00

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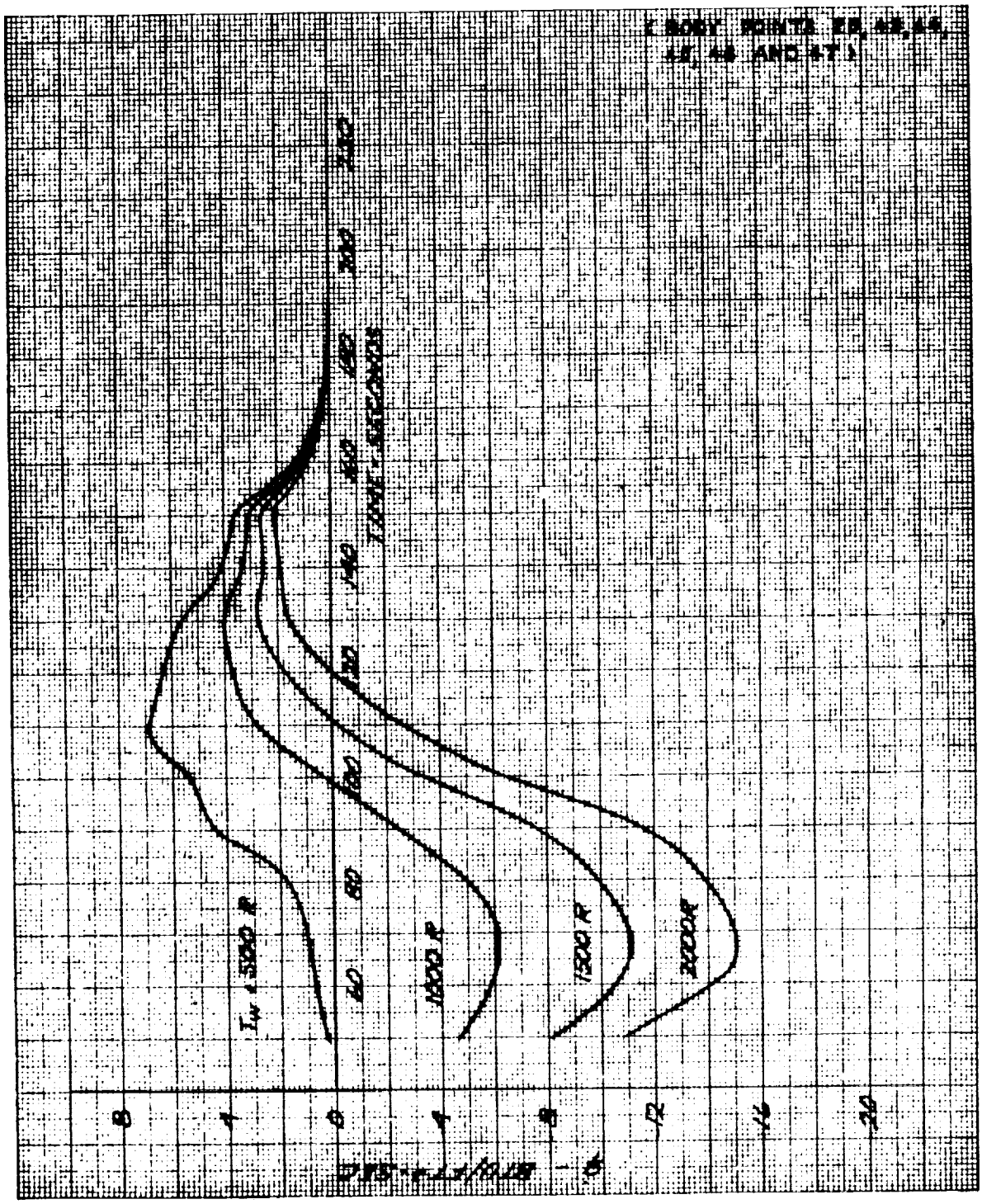

Figure 34. Saturn V Boost Heating, X_c = 20.00

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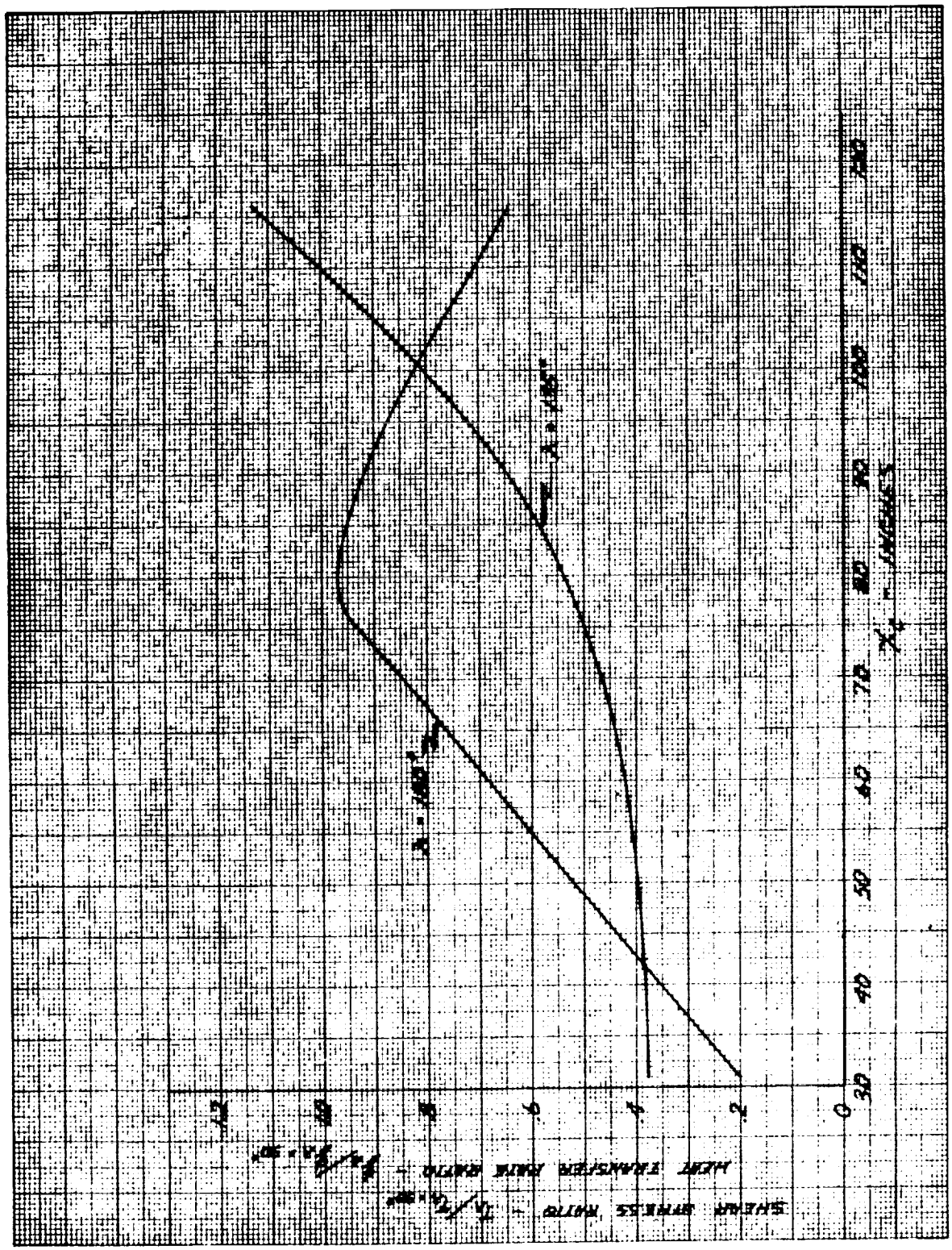

Figure 35. Shear Stress Distribution and Heating in Separated Wake Region

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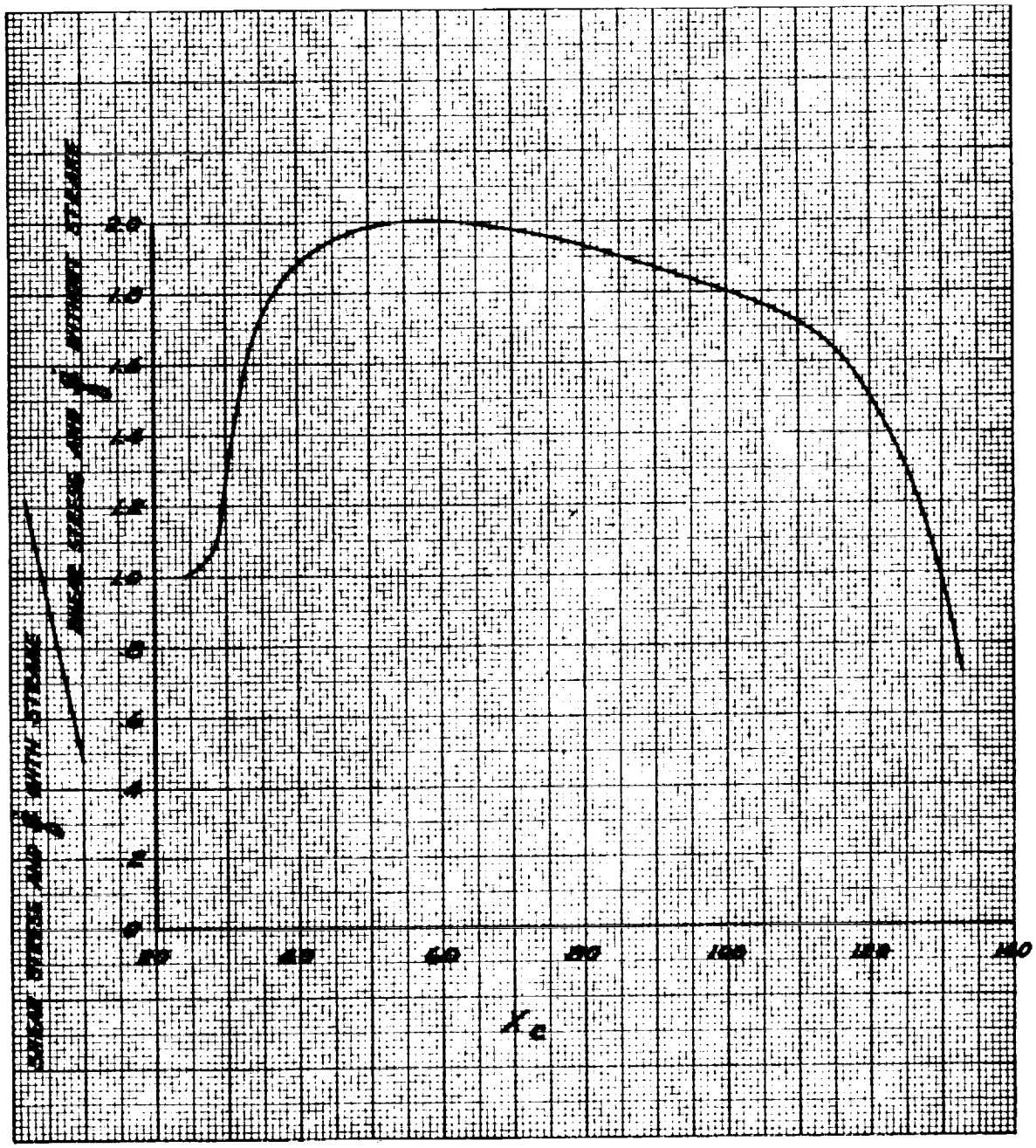

Figure 36. Effect of Aerodynamic Strakes on Afterbody Heating Rate and Shear Stress Distribution (λ = 135° and 180°)

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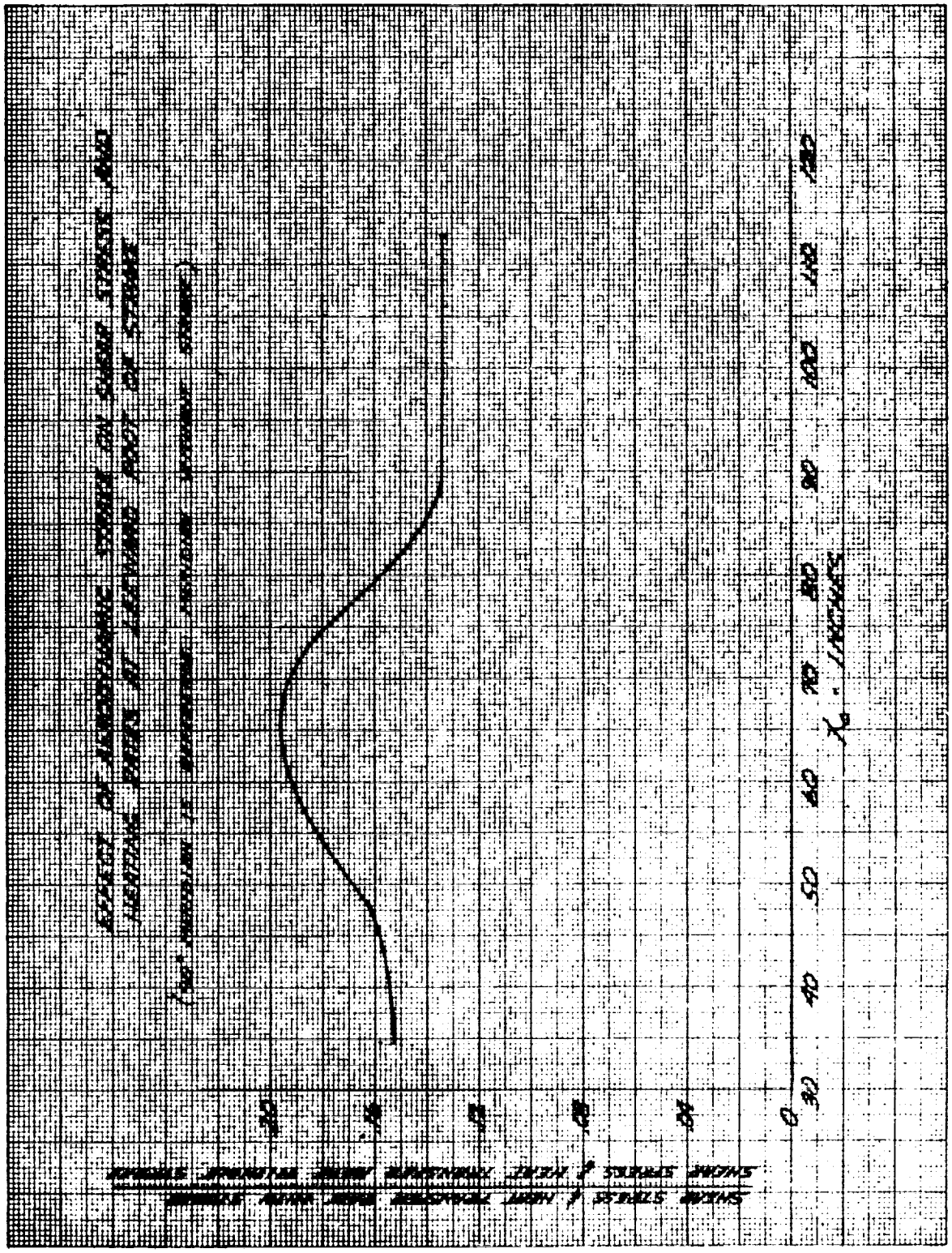

Figure 36A. Effect of Aerodynamic Strake on Shear Stress and Heating Rates at Leeward Root of Strake

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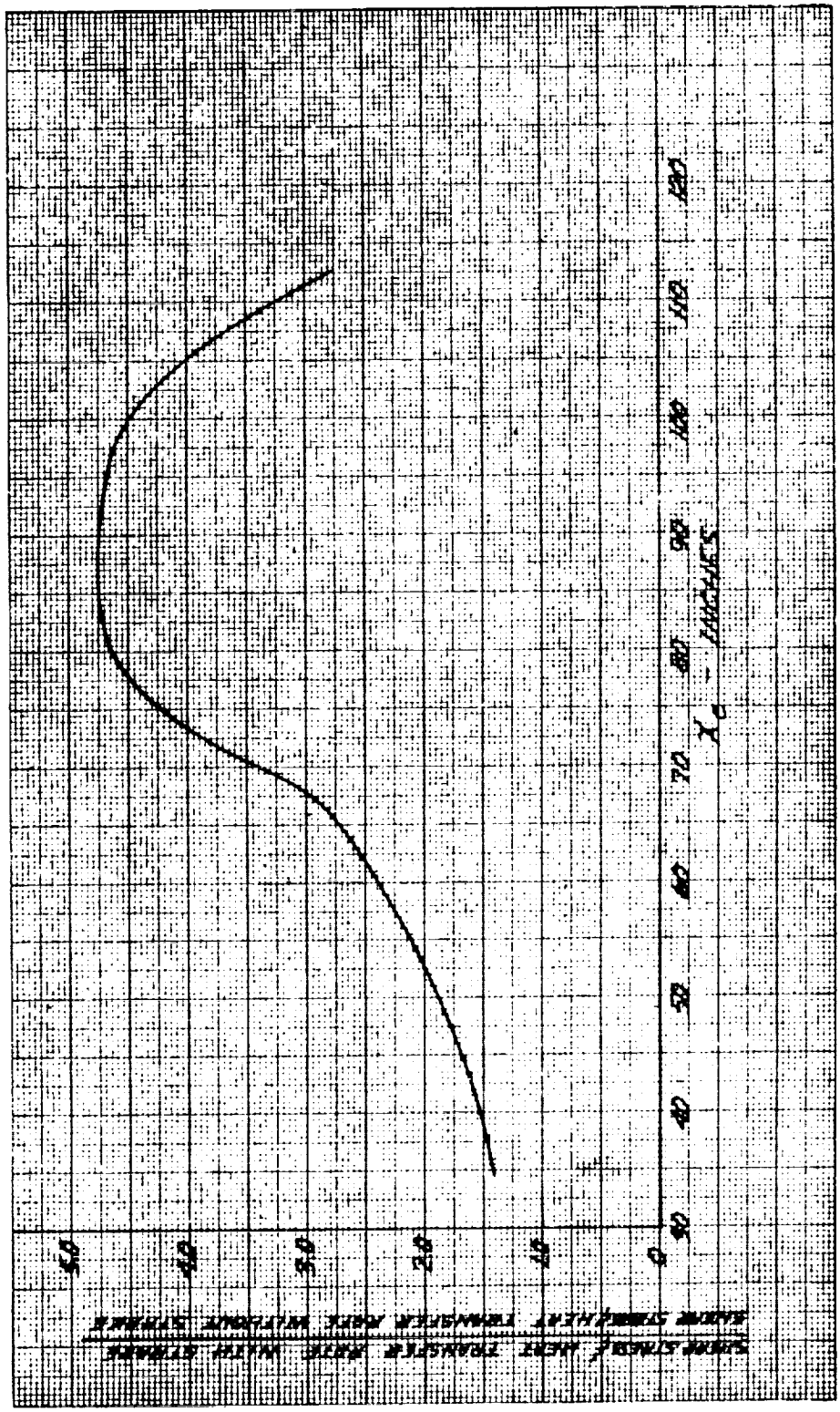

Figure 36B. Effect of Aerodynamic Strake on Shear Stress and Heating Rates at Windward Root of Strake

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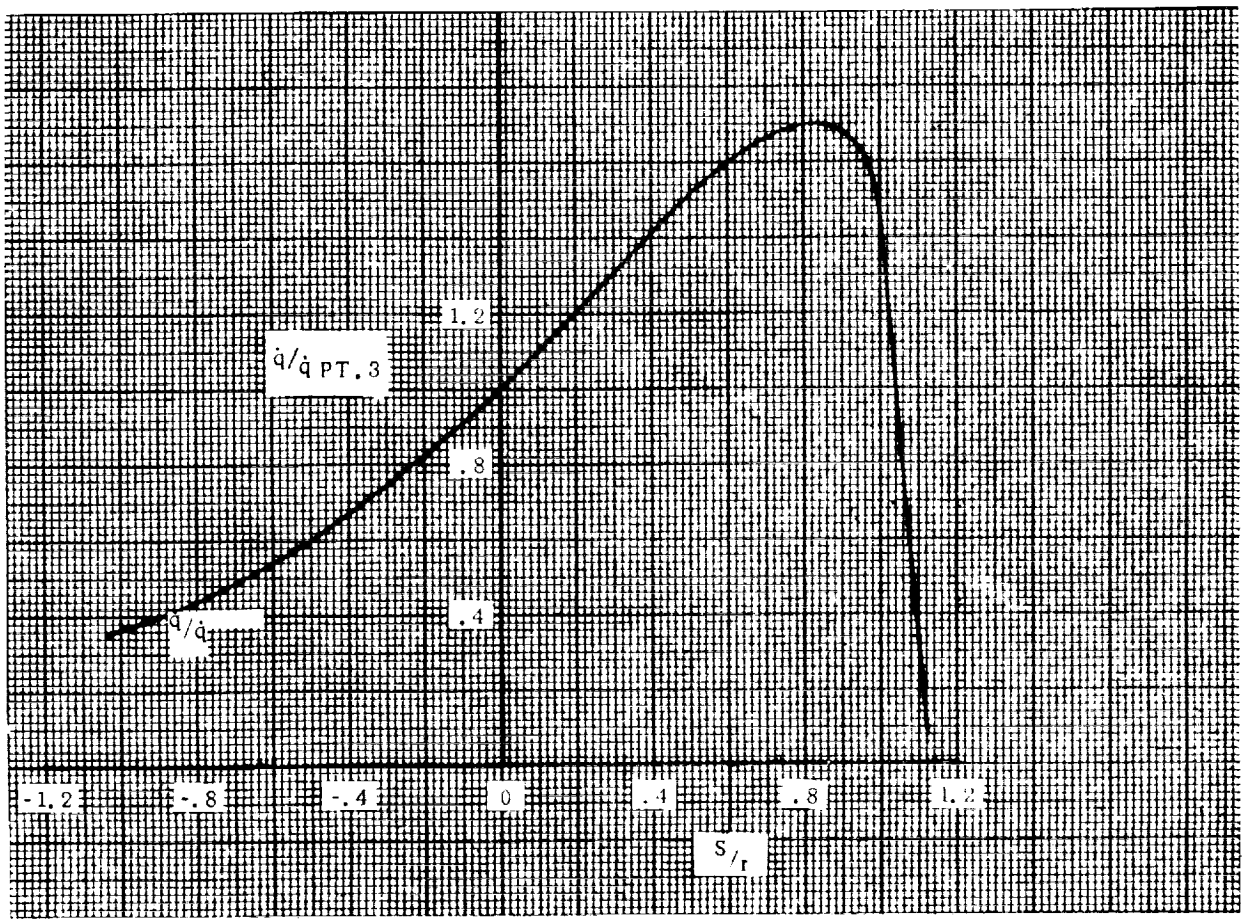

Figure 37. Trajectory HSE-1, Non-Equilibrium Radiation Distribution, $\lambda = 0°$

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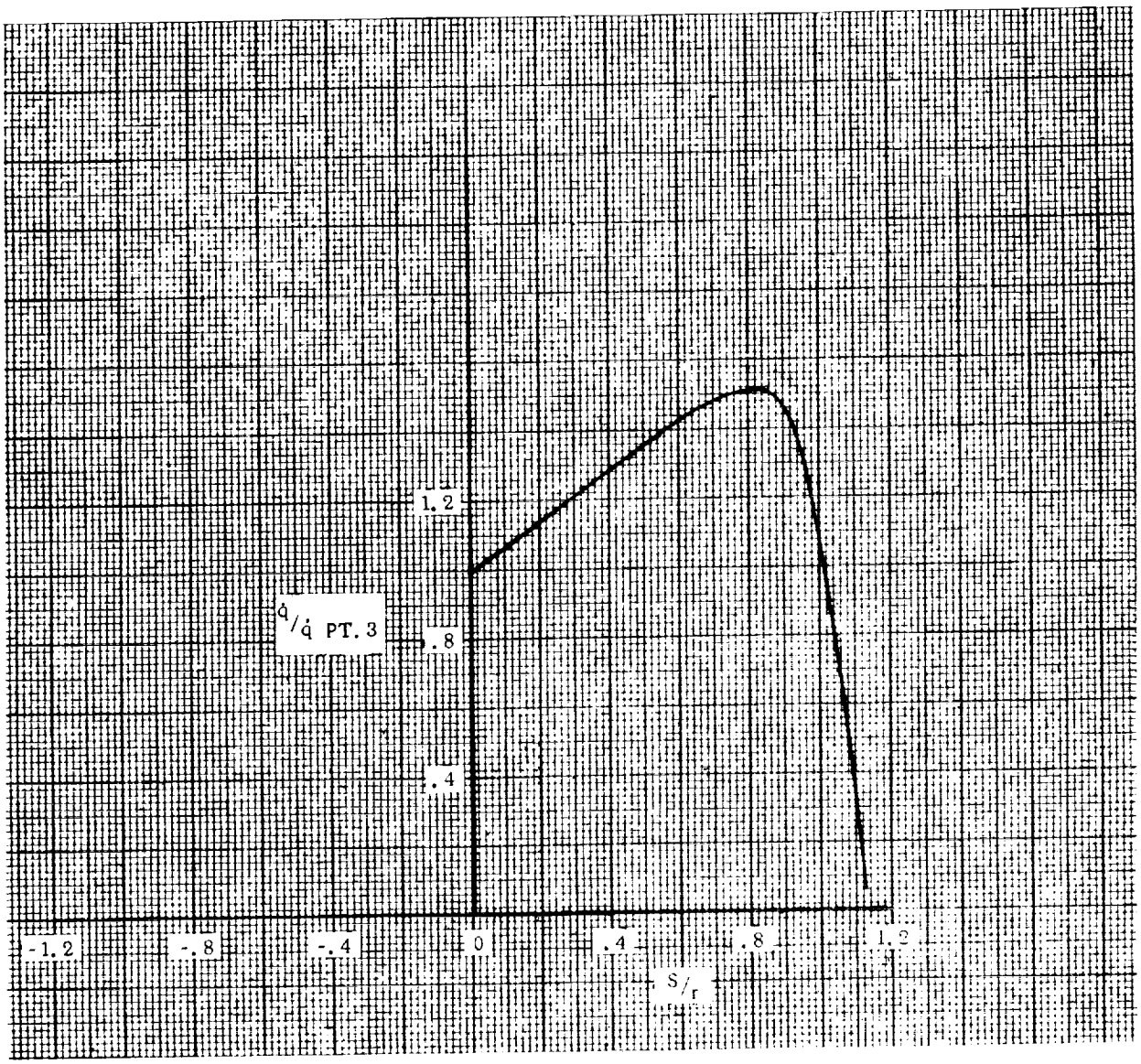

Figure 38. Trajectory HSE-1, Non-Equilibrium Radiation Distribution, $\lambda = 22.5°$

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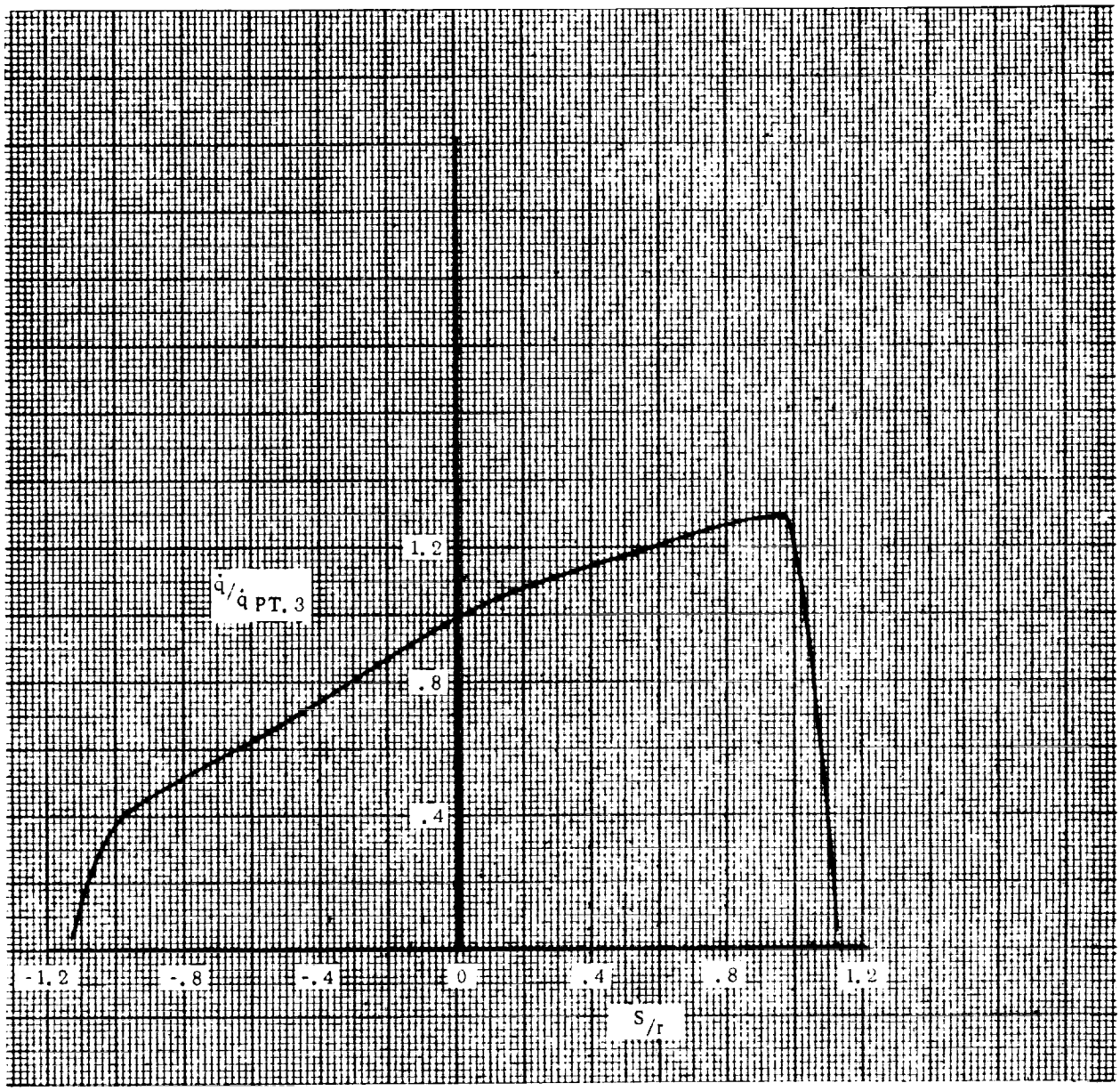

Figure 39. Trajectory HSE-1, Non-Equilibrium Radiation Distribution, $\lambda = 45°$

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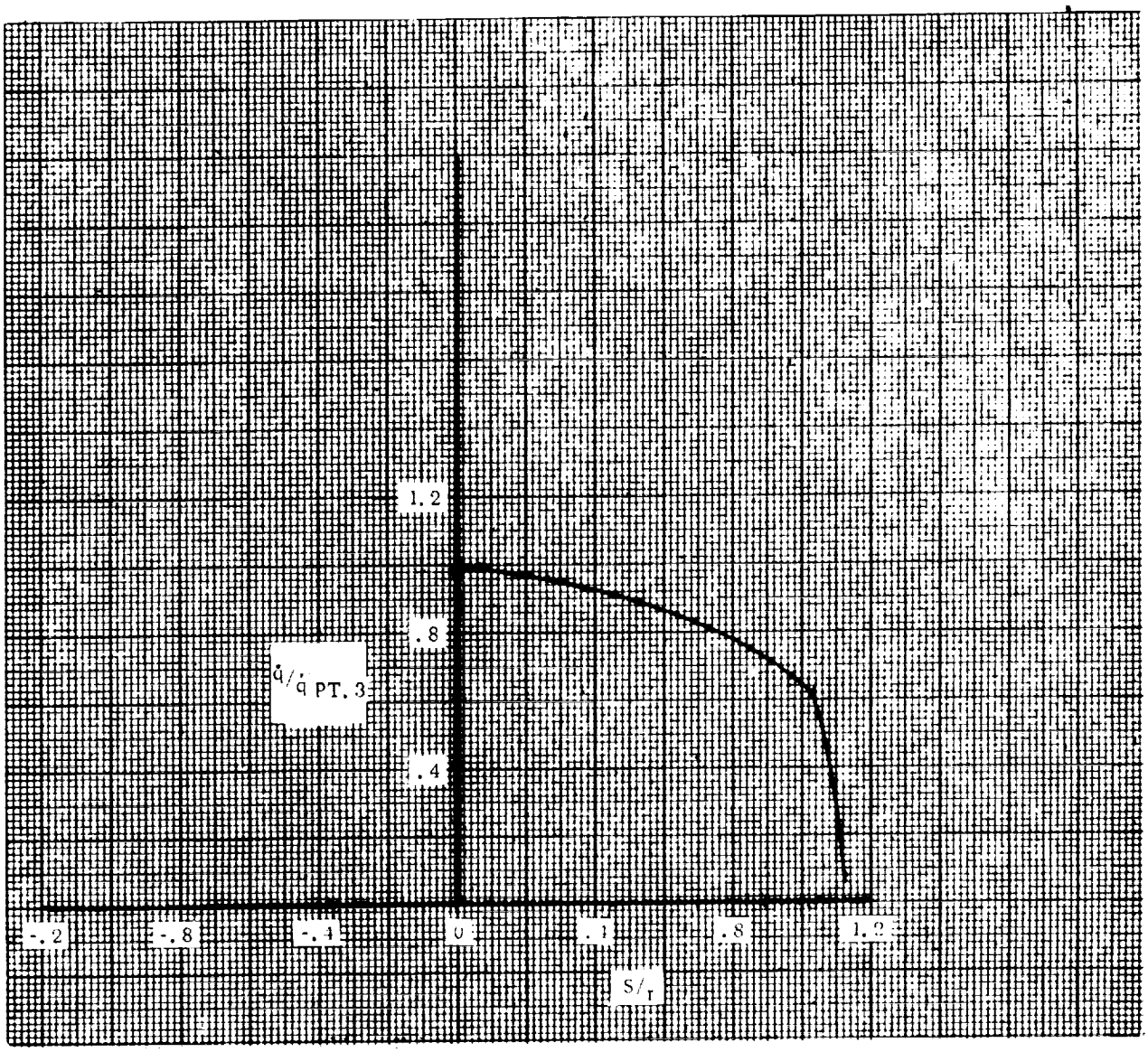

Figure 40. Trajectory HSE-1, Non-Equilibrium Radiation Distribution, λ = 90°

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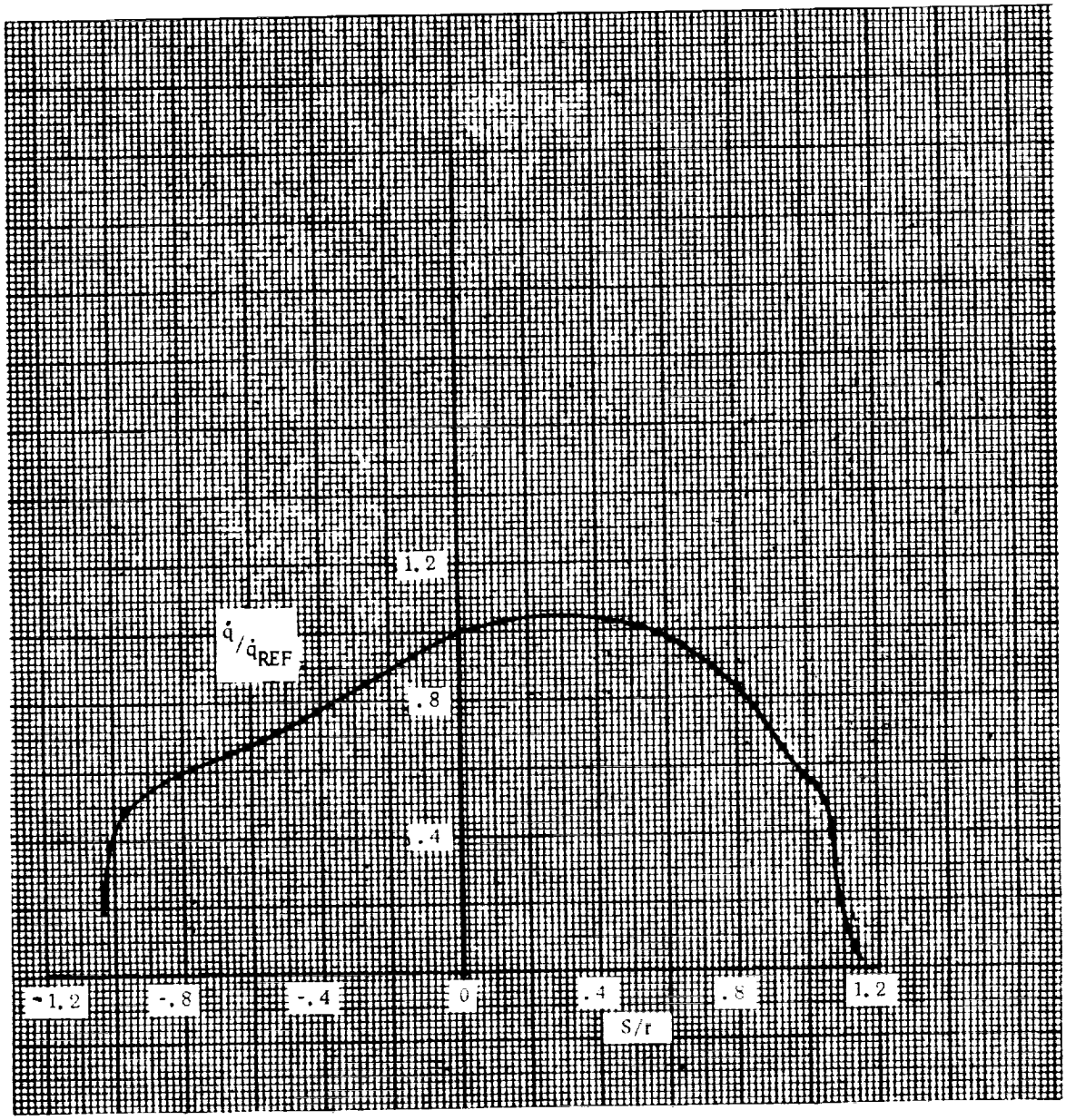

Figure 41. Trajectory HSE-2, Equilibrium Radiation Distribution, $\lambda = 0°$

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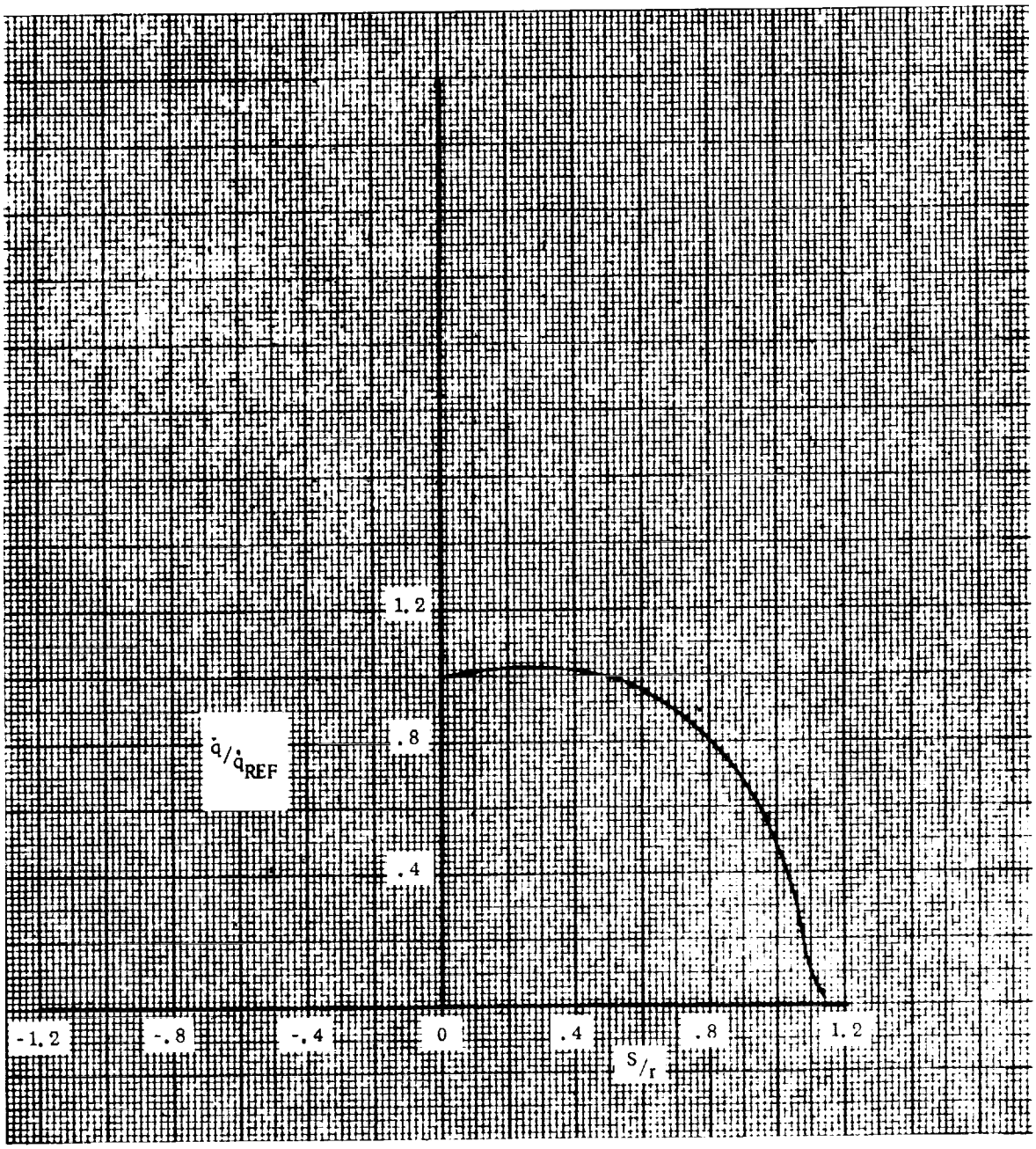

Figure 42. Trajectory HSE-2, Equilibrium Radiation Distribution, $\lambda = 22.5°$

[redacted]

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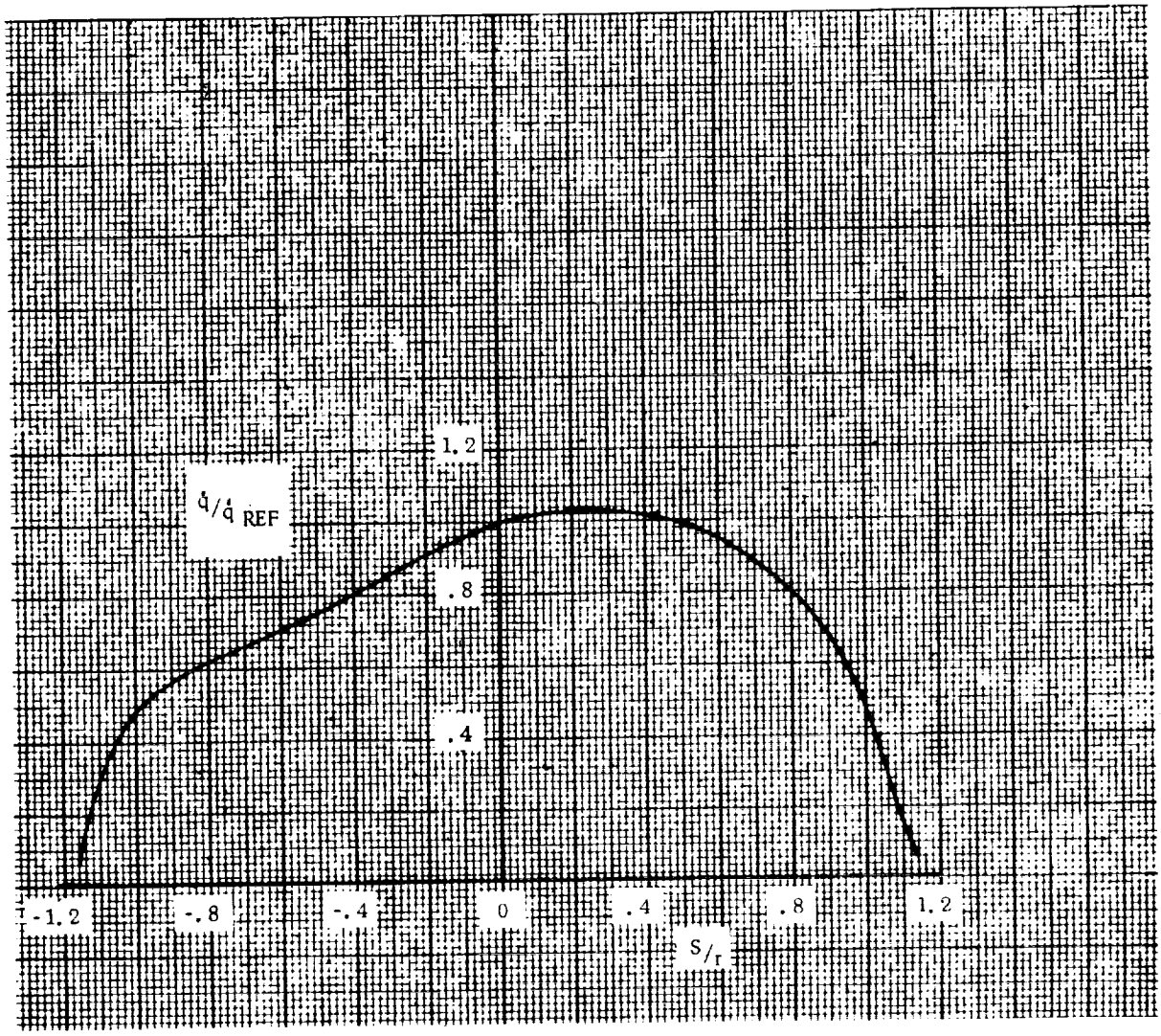

Figure 43. Trajectory HSE-2, Equilibrium Radiation Distribution, $\lambda = 45°$

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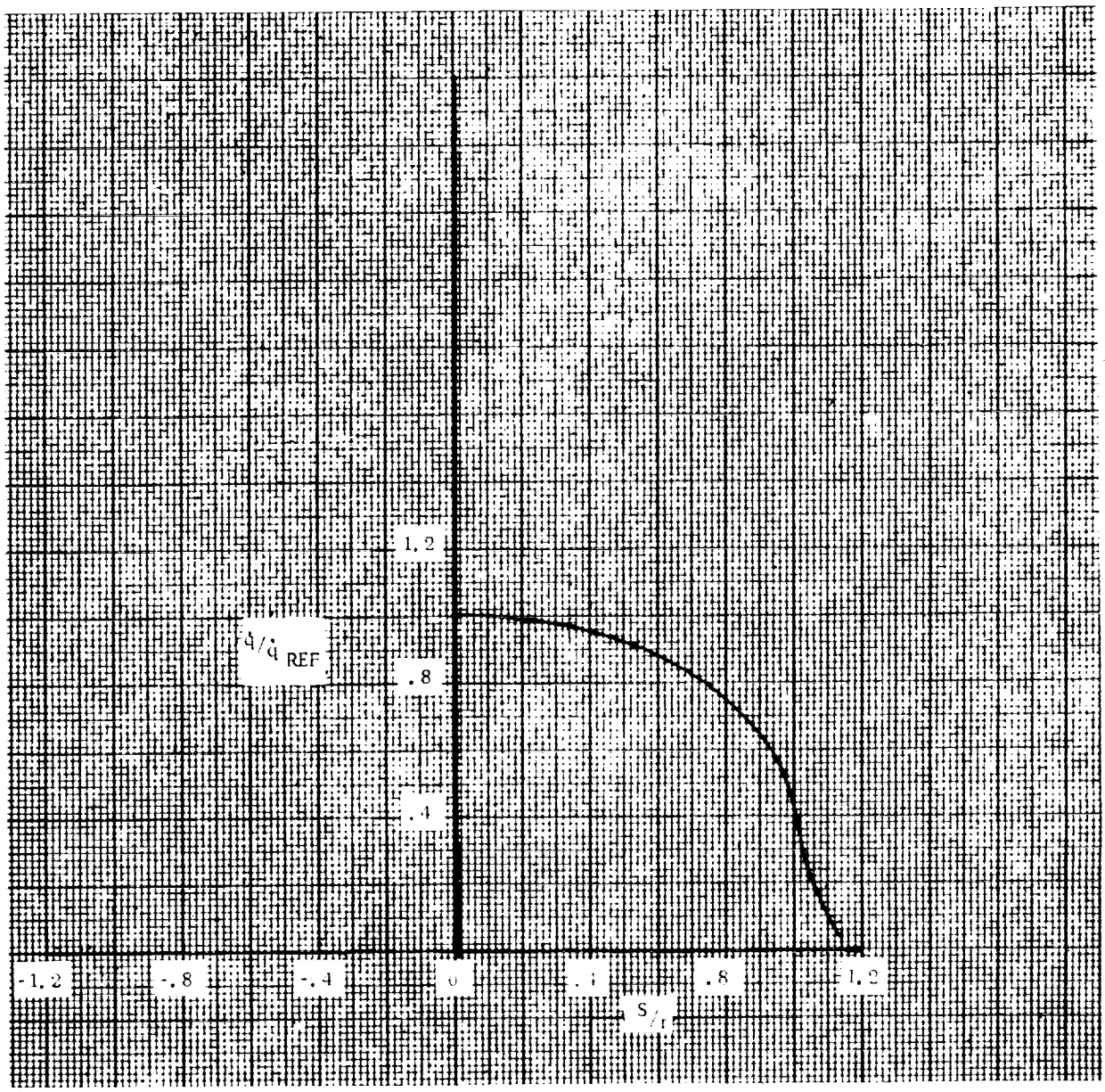

Figure 44. Trajectory HSE-2, Equilibrium Radiation Distribution, $\lambda = 90°$

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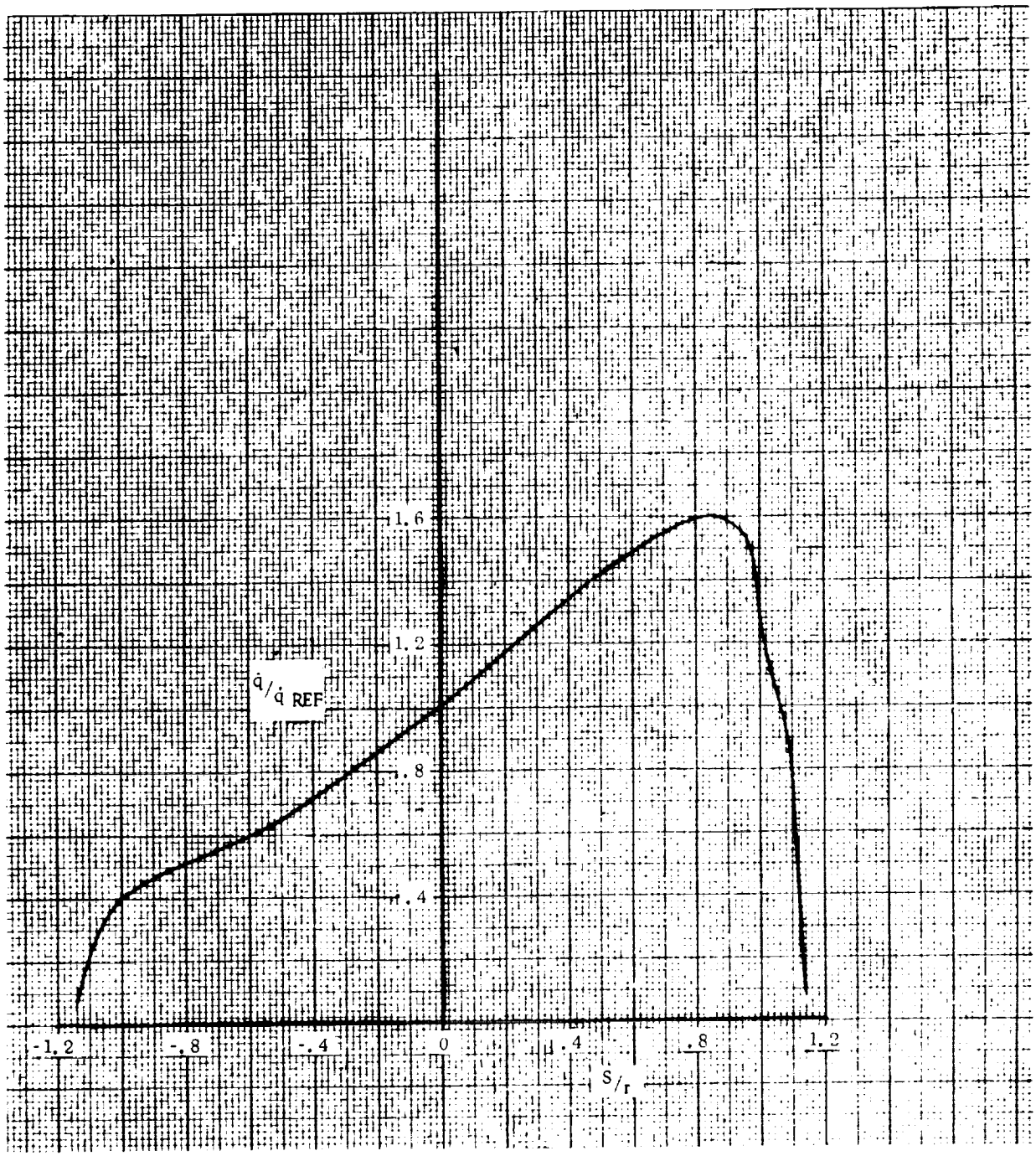

Figure 45. Trajectory HSE-2, Non-Equilibrium Radiation Distribution, $\lambda = 0°$

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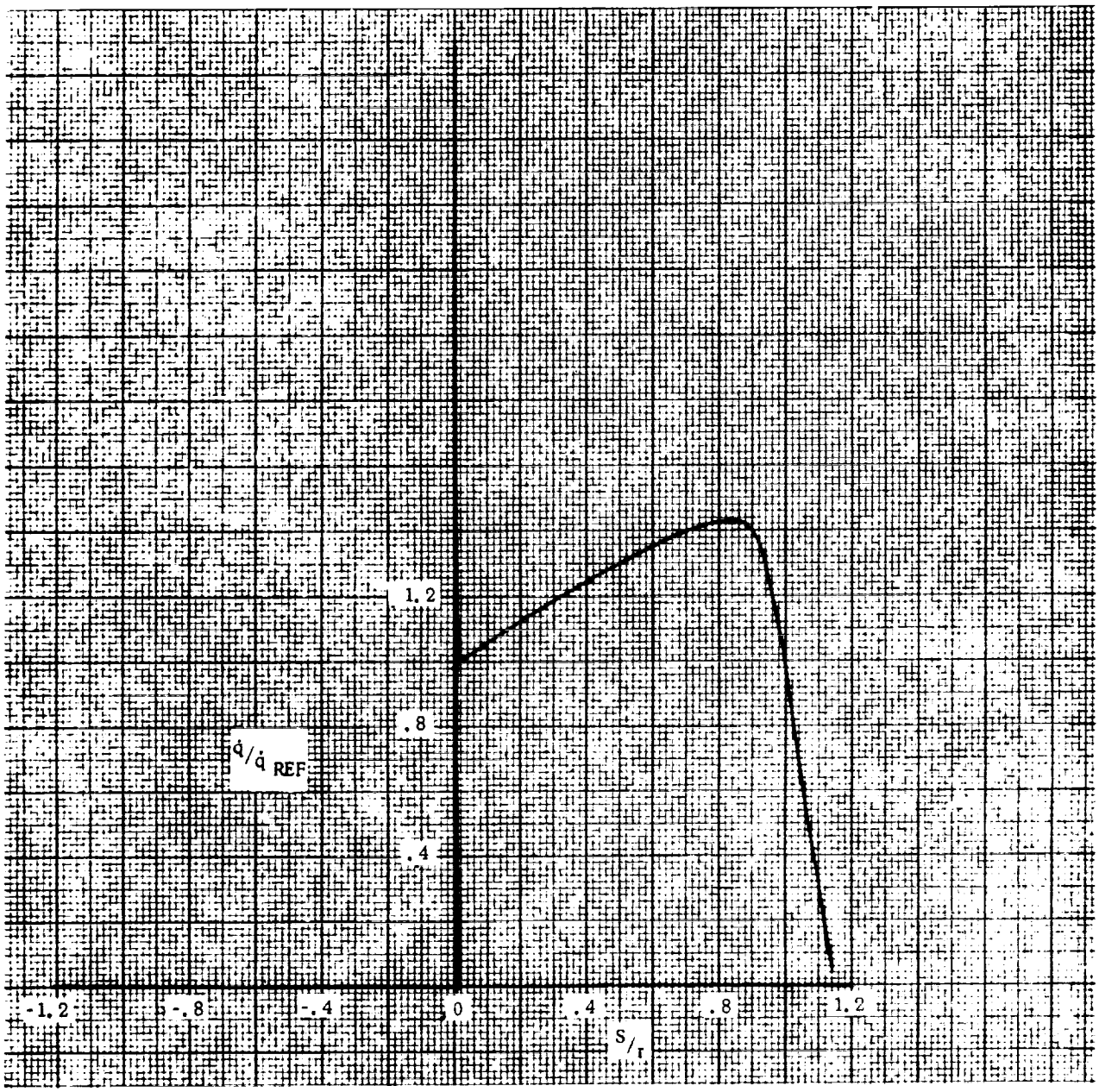

Figure 46. Trajectory HSE-2, Non-Equilibrium Radiation Distribution, λ = 22.5°

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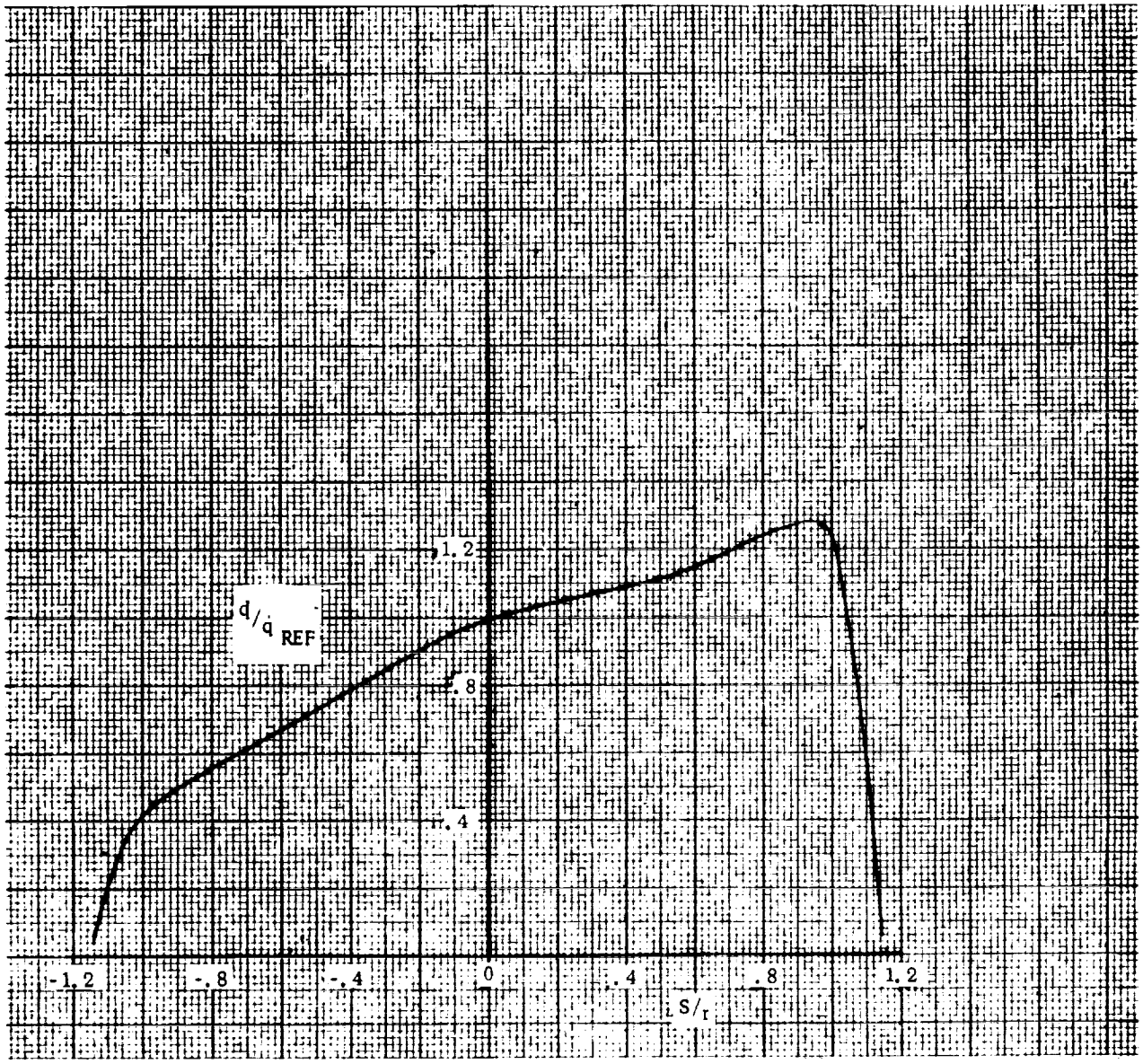

Figure 47. Trajectory HSE-2, Non-Equilibrium Radiation Distribution, $\lambda = 45°$

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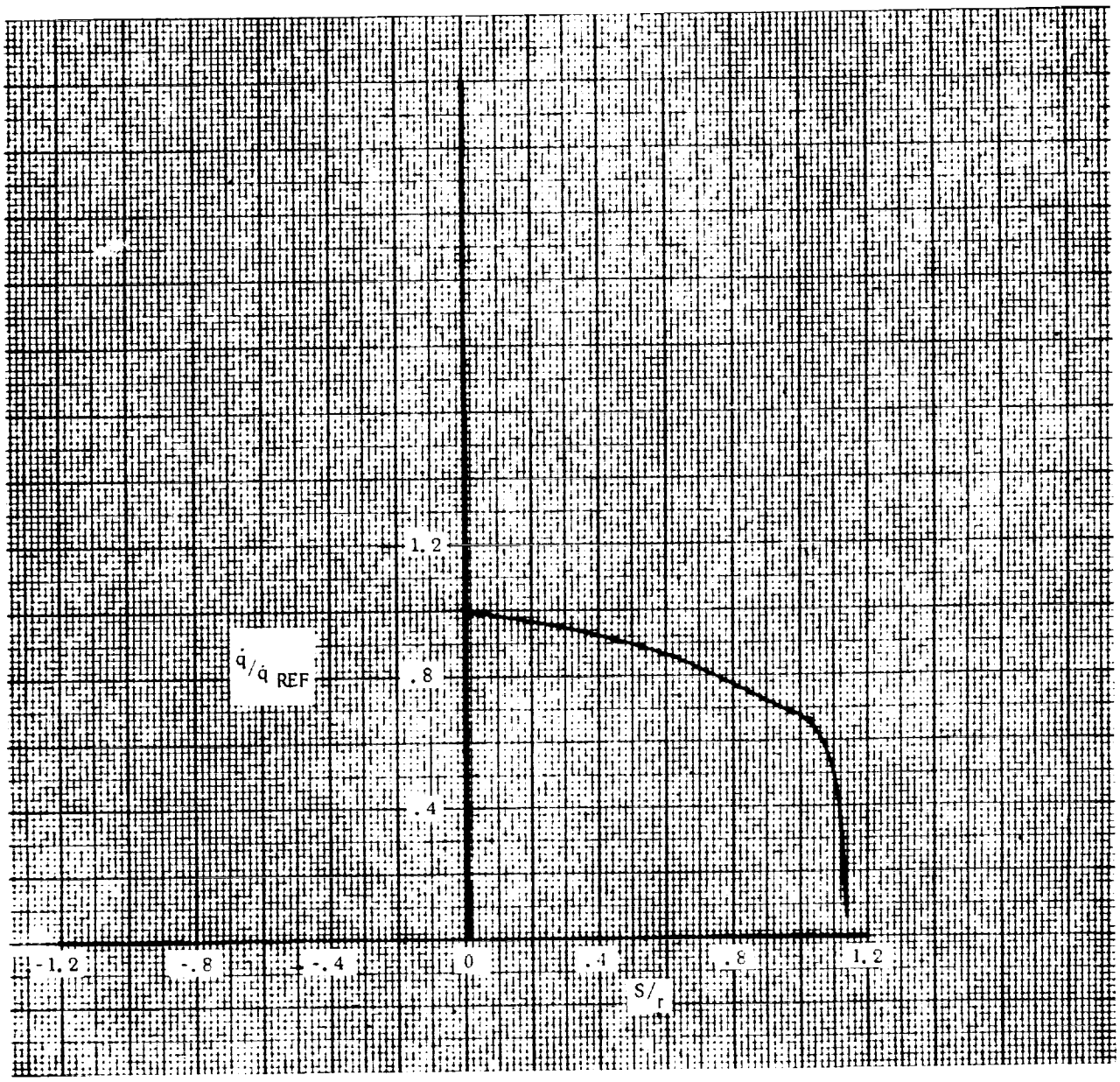

Figure 48. Trajectory HSE-2, Non-Equilibrium Radiation Distribution, $\lambda = 90°$

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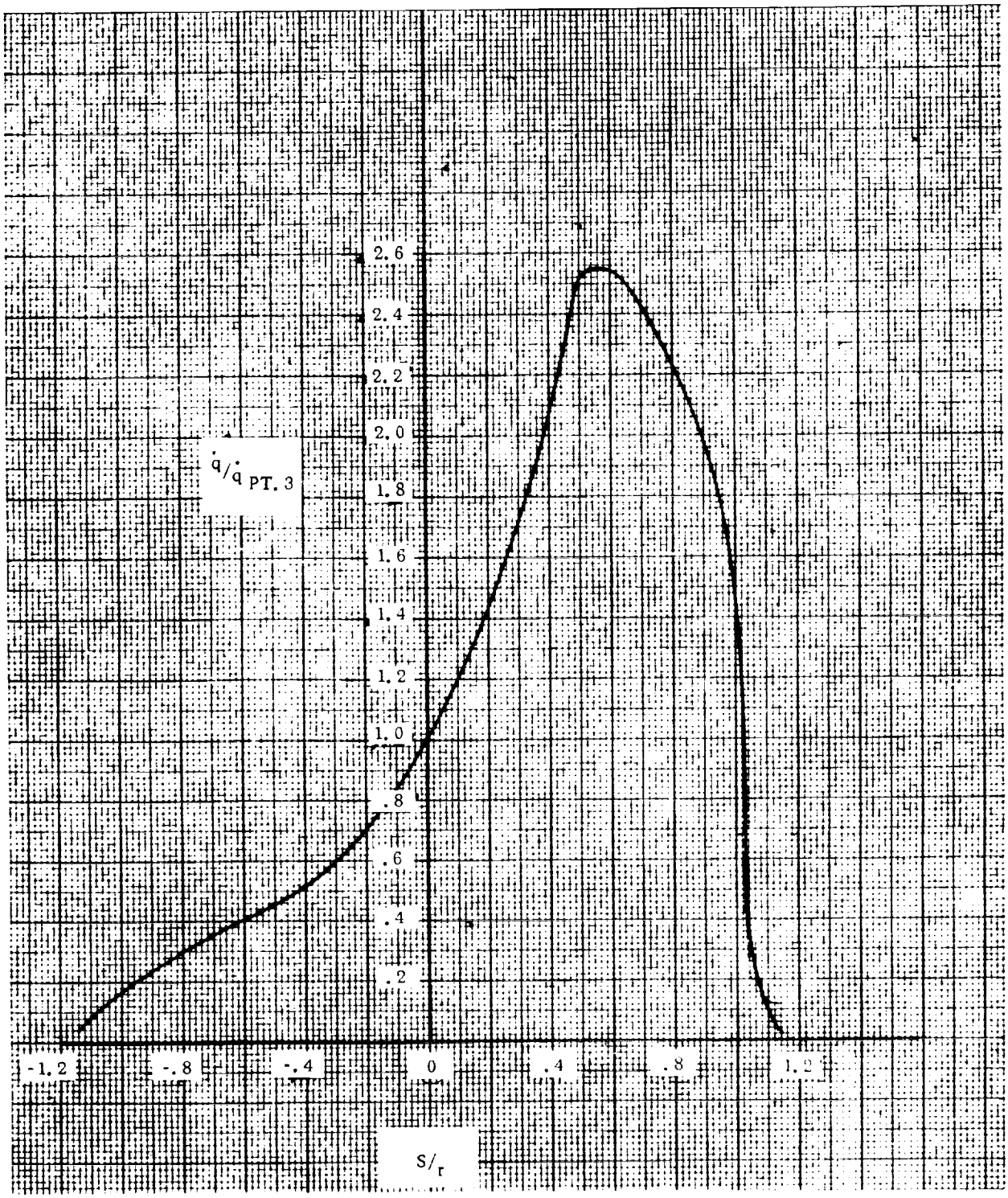

Figure 49. Trajectory HSE-3A, Equilibrium Radiation Distribution, $\lambda = 0°$

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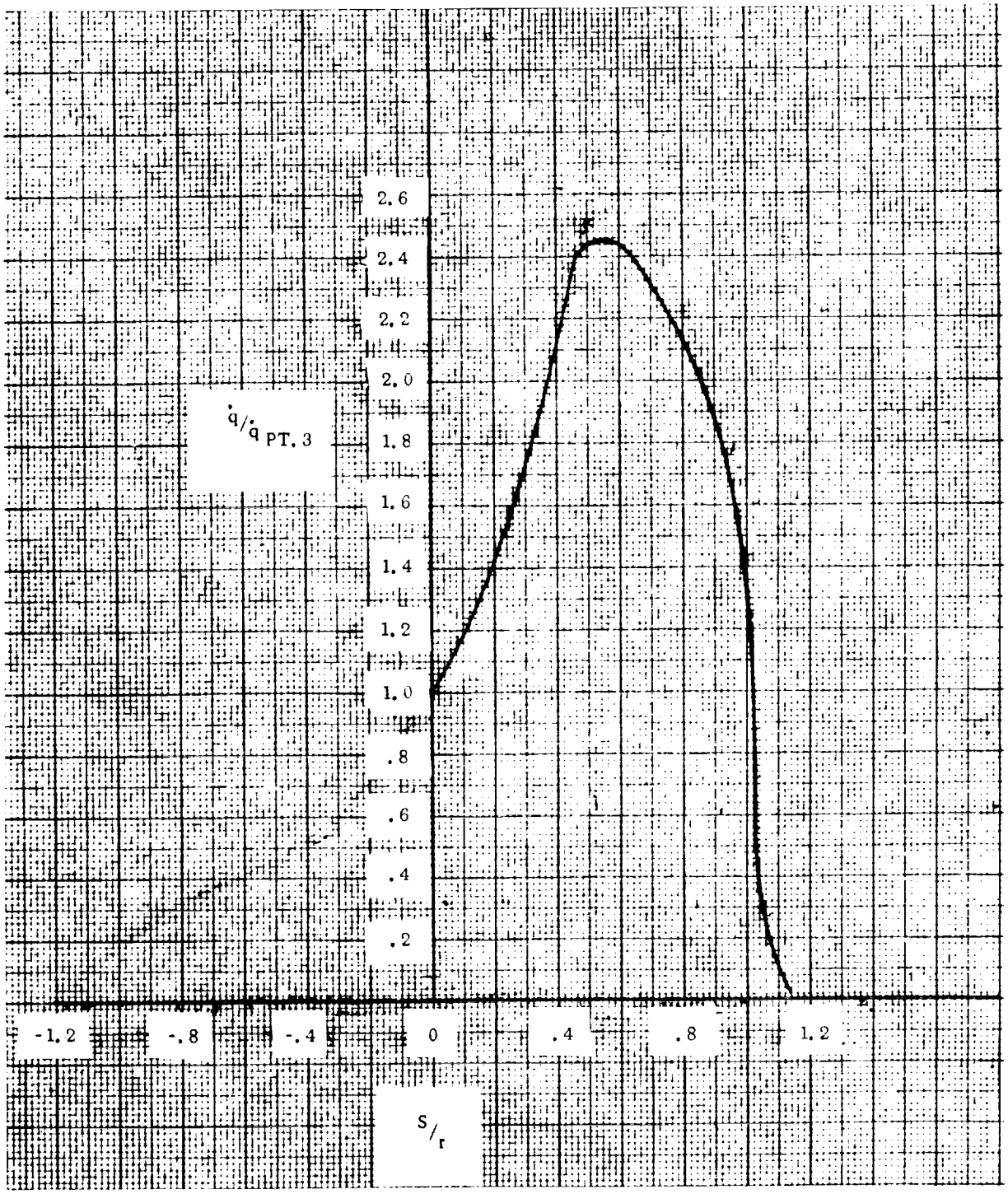

Figure 50. Trajectory HSE-3A, Equilibrium Radiation Distribution, λ = 22.5°

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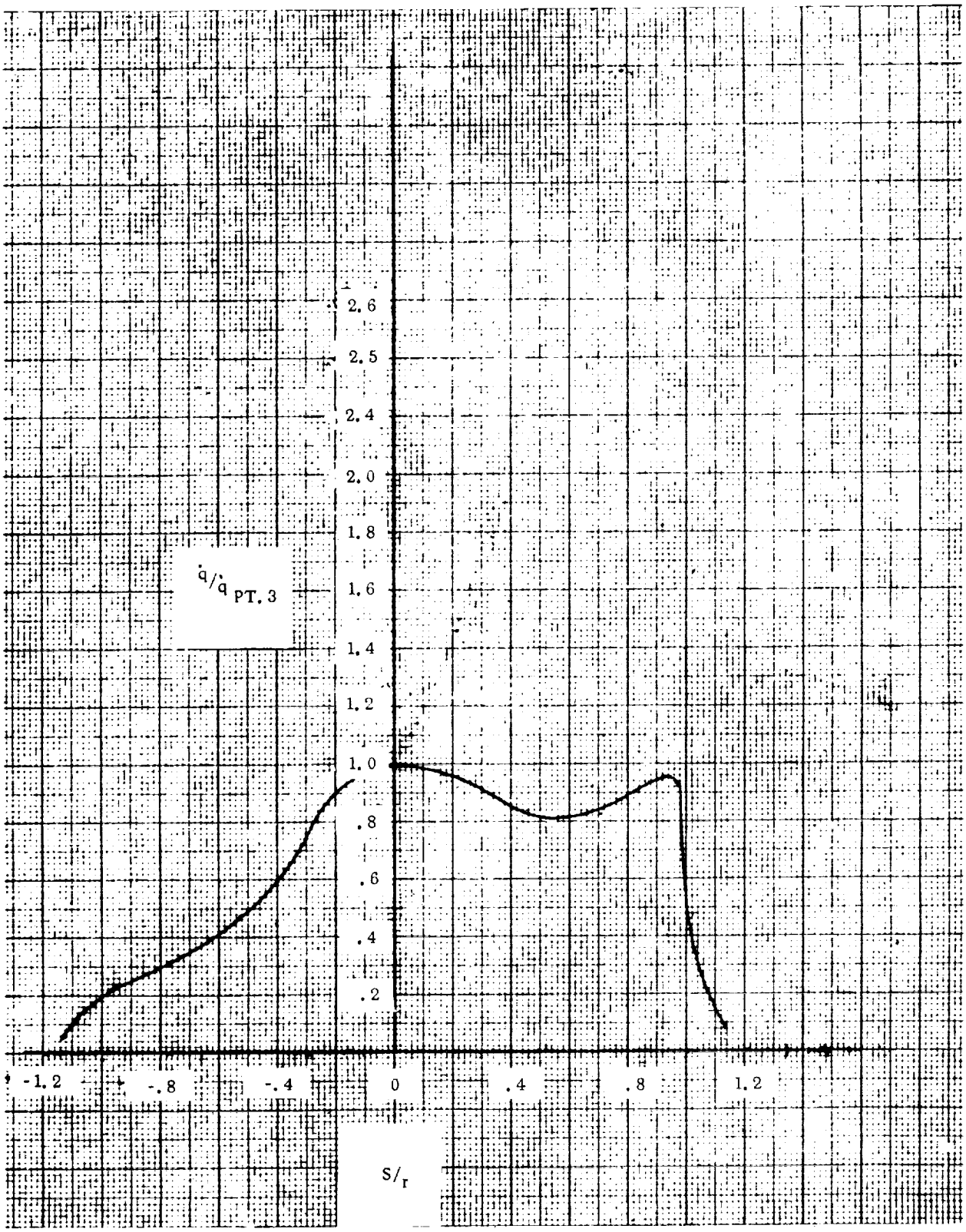

Figure 51. Trajectory HSE-3A, Equilibrium Radiation Distribution, $\lambda = 45°$

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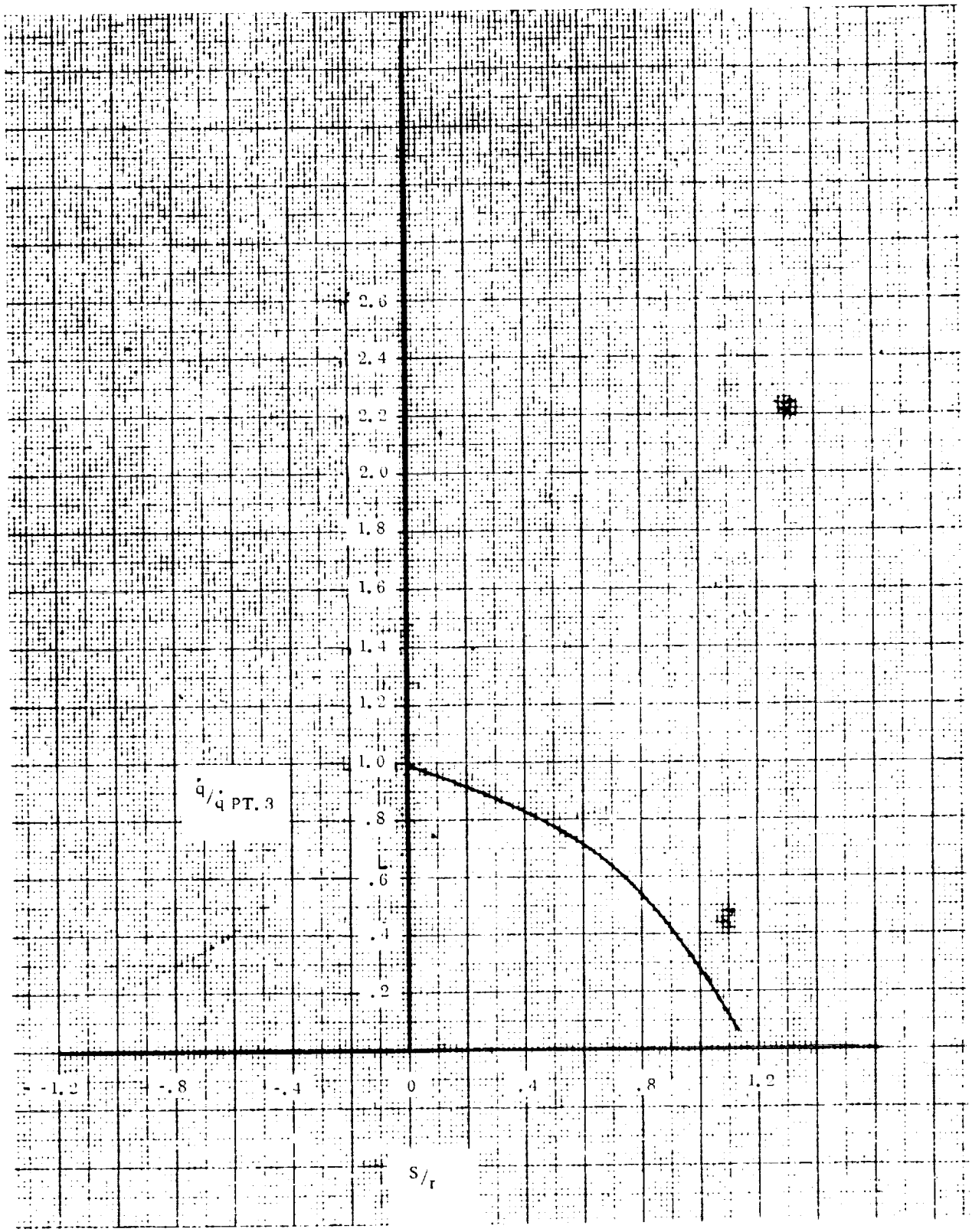

Figure 52. Trajectory HSE-3A, Equilibrium Radiation Distribution, $\lambda = 90°$

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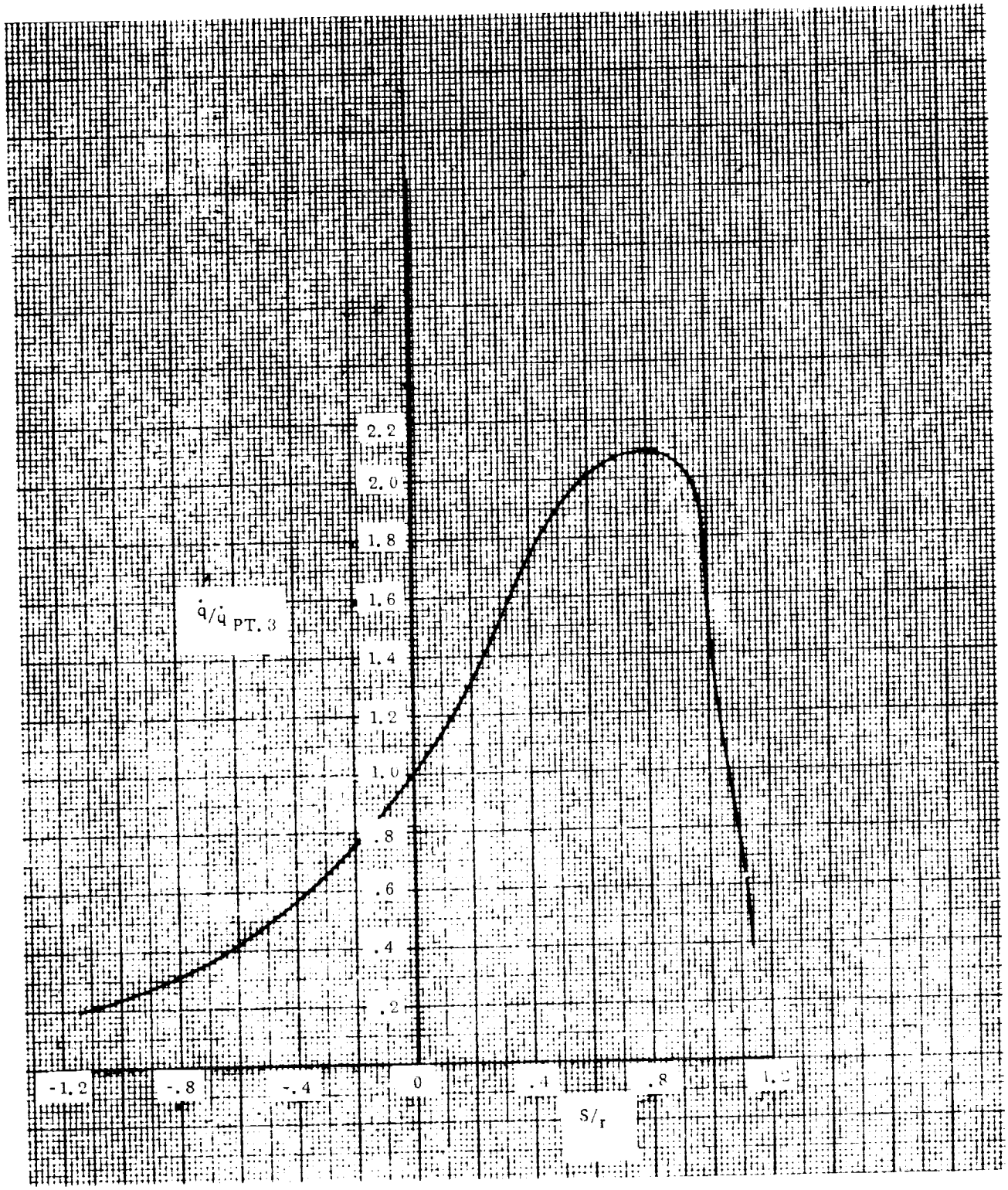

Figure 53. Trajectory HSE-3A, Non-Equilibrium Radiation Distribution, $\lambda = 0°$

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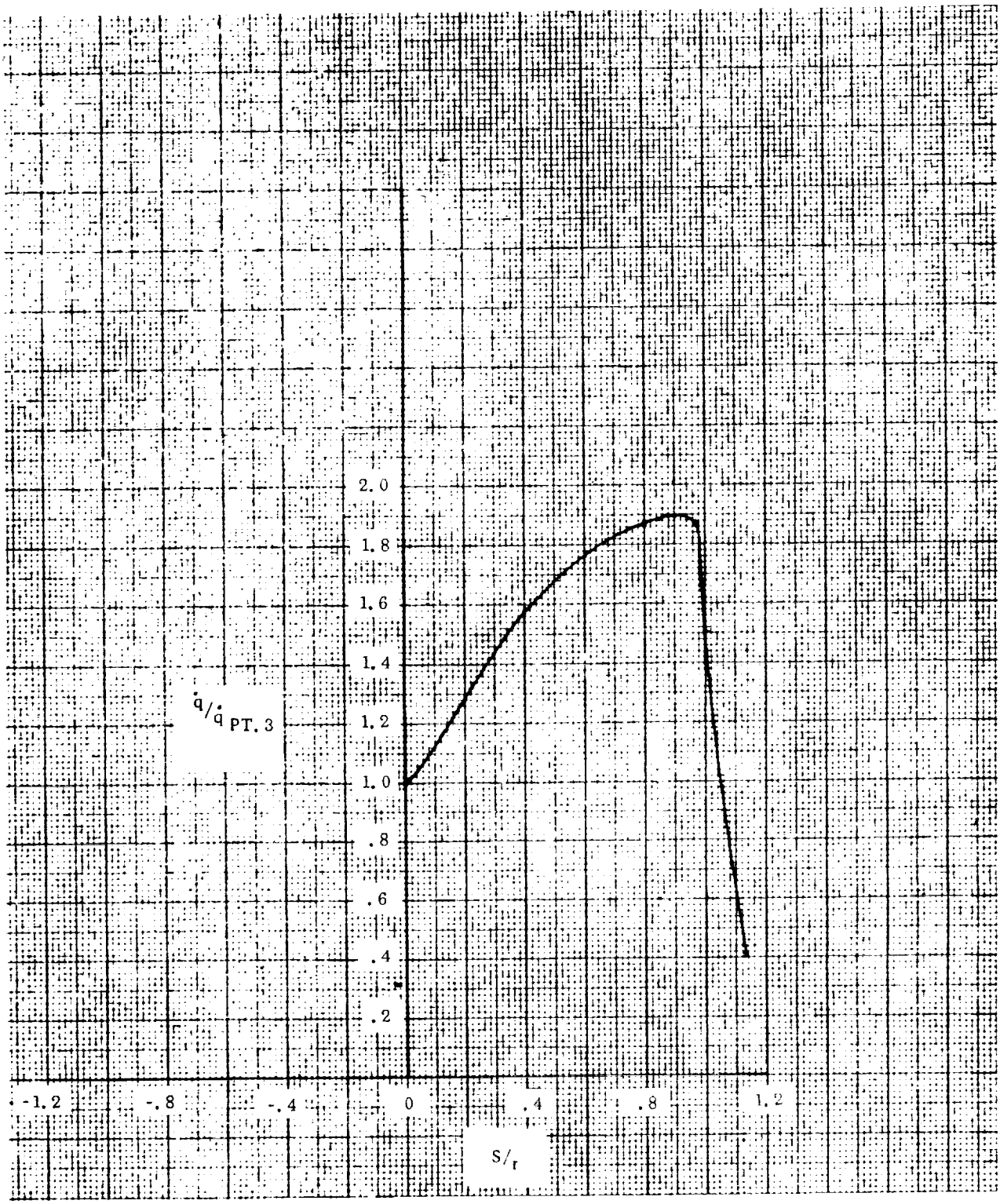

Figure 54. Trajectory HSE-3A, Non-Equilibrium Radiation Distribution, $\lambda = 22.5°$

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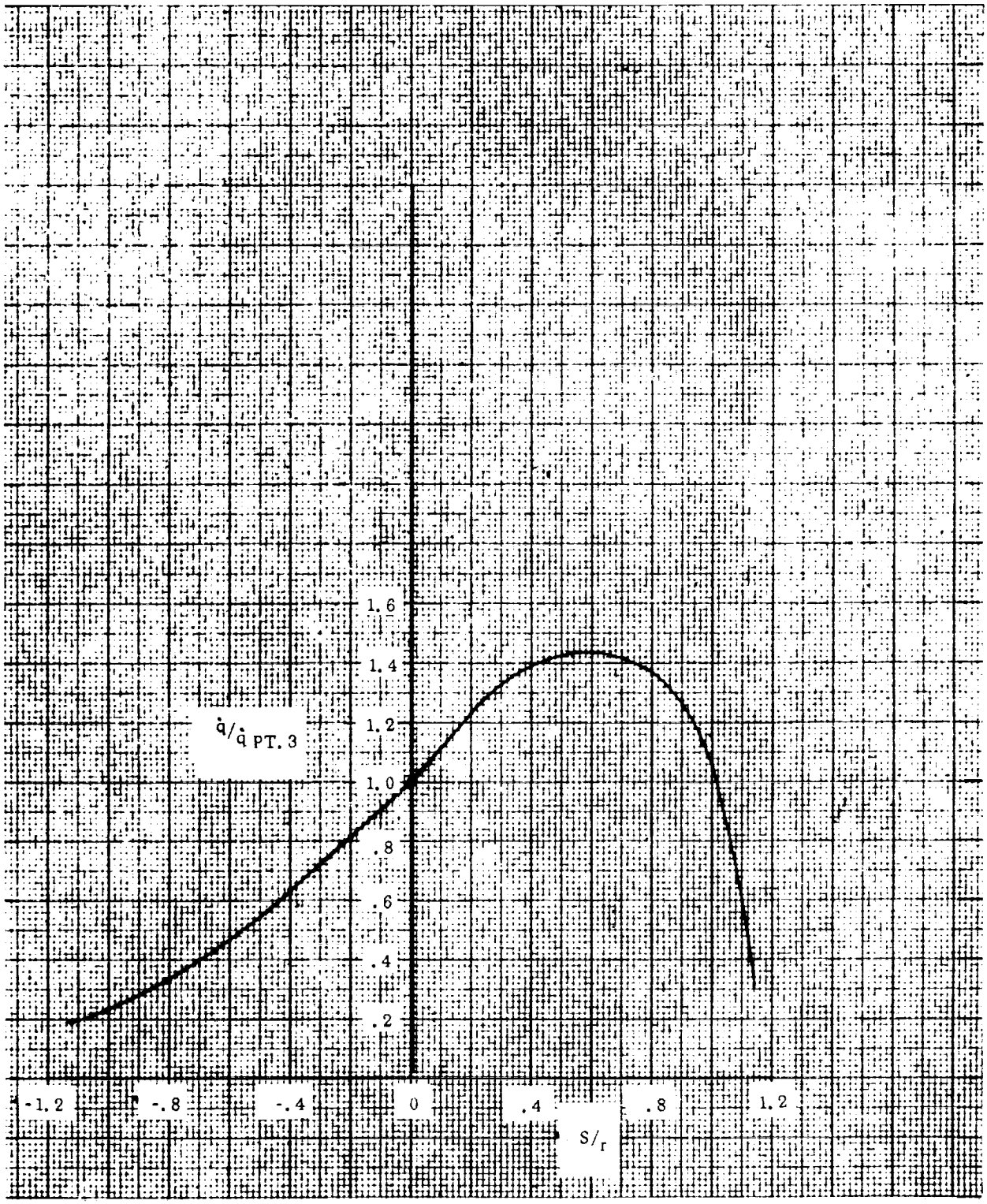

Figure 55. Trajectory HSE-3A, Non-Equilibrium Radiation Distribution, $\lambda = 45°$

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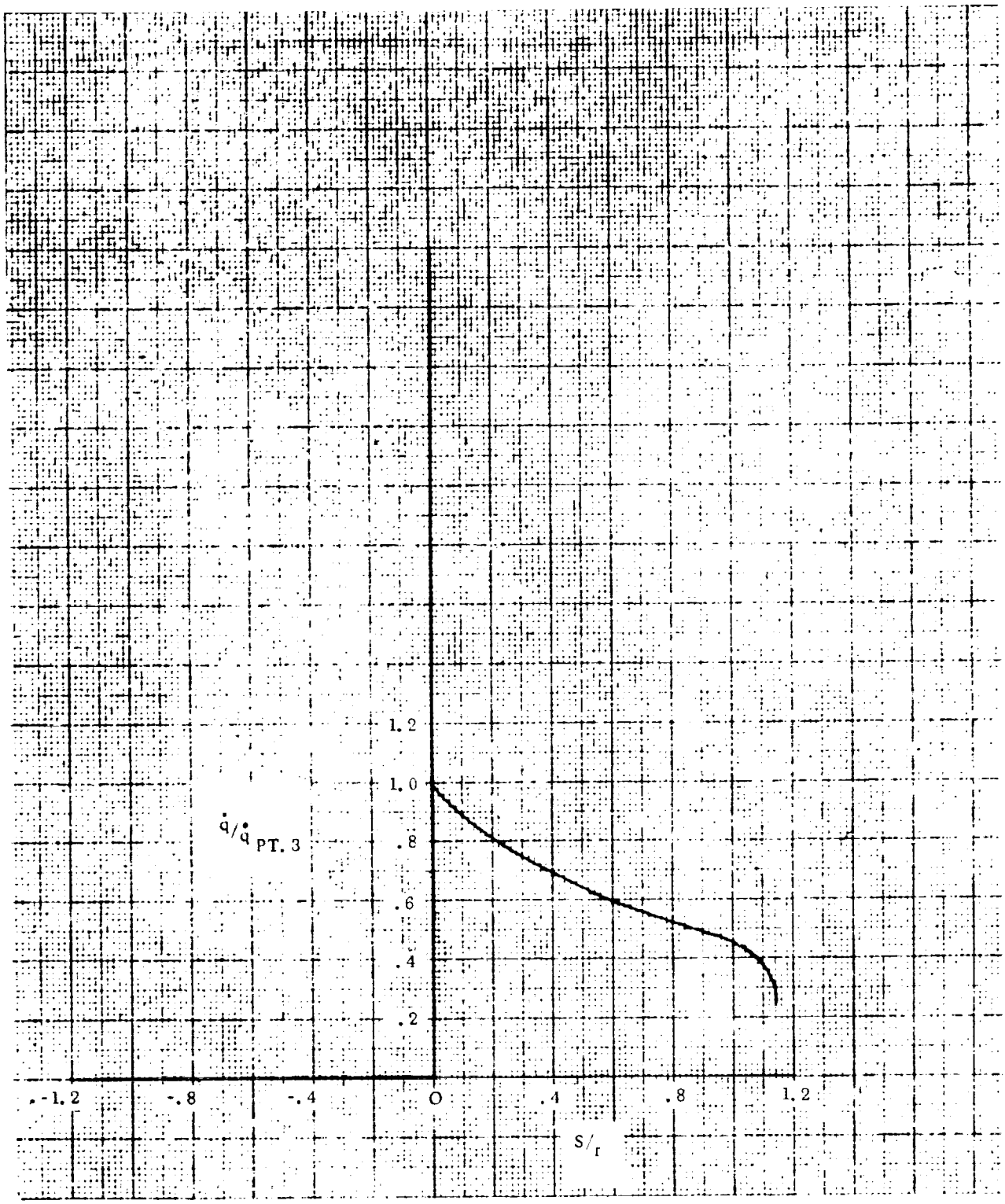

Figure 56. Trajectory HSE-3A, Non-Equilibrium Radiation Distribution, $\lambda = 90°$

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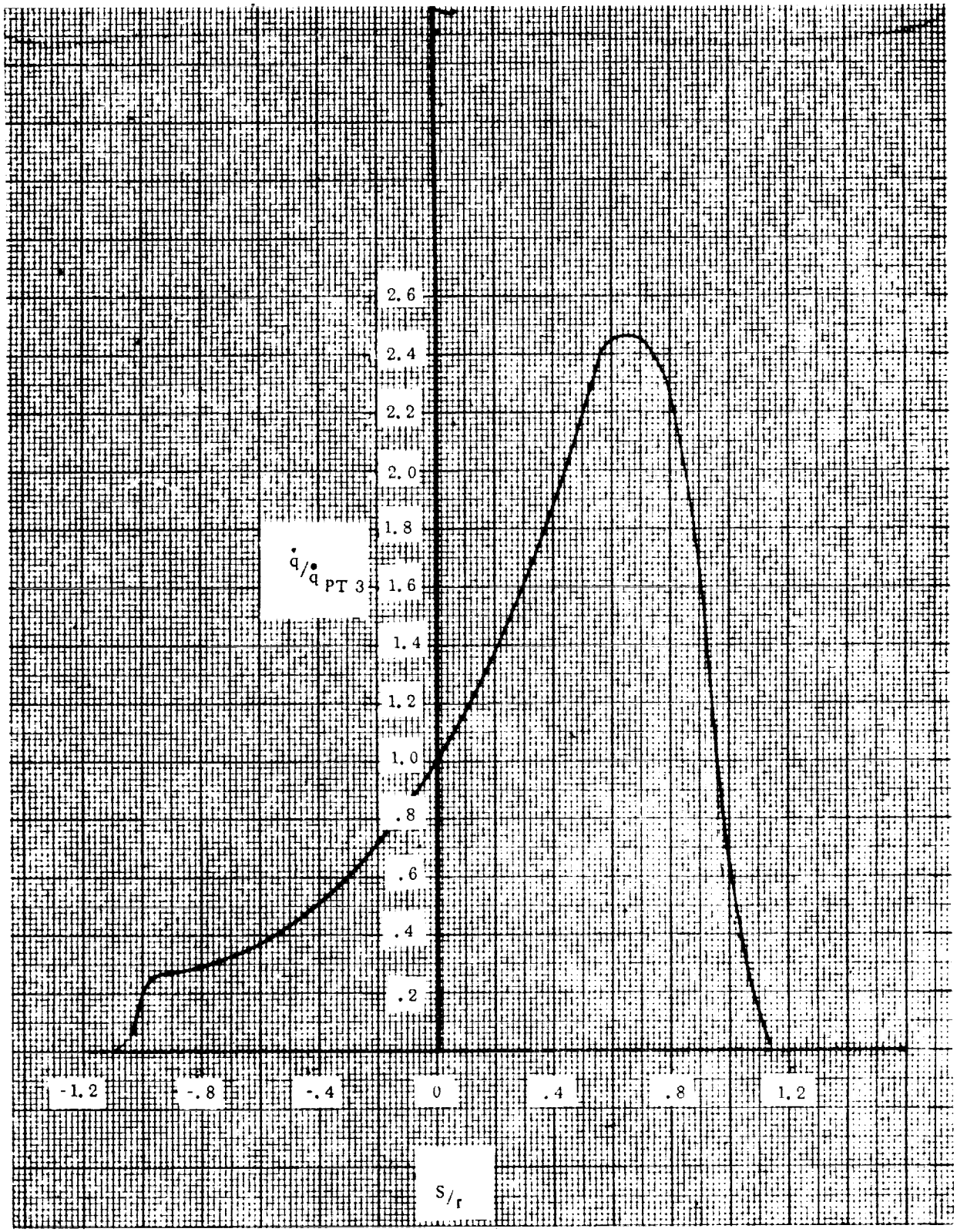

Figure 57. Trajectory HSE-4A, Equilibrium Radiation Distribution, $\lambda = 0°$

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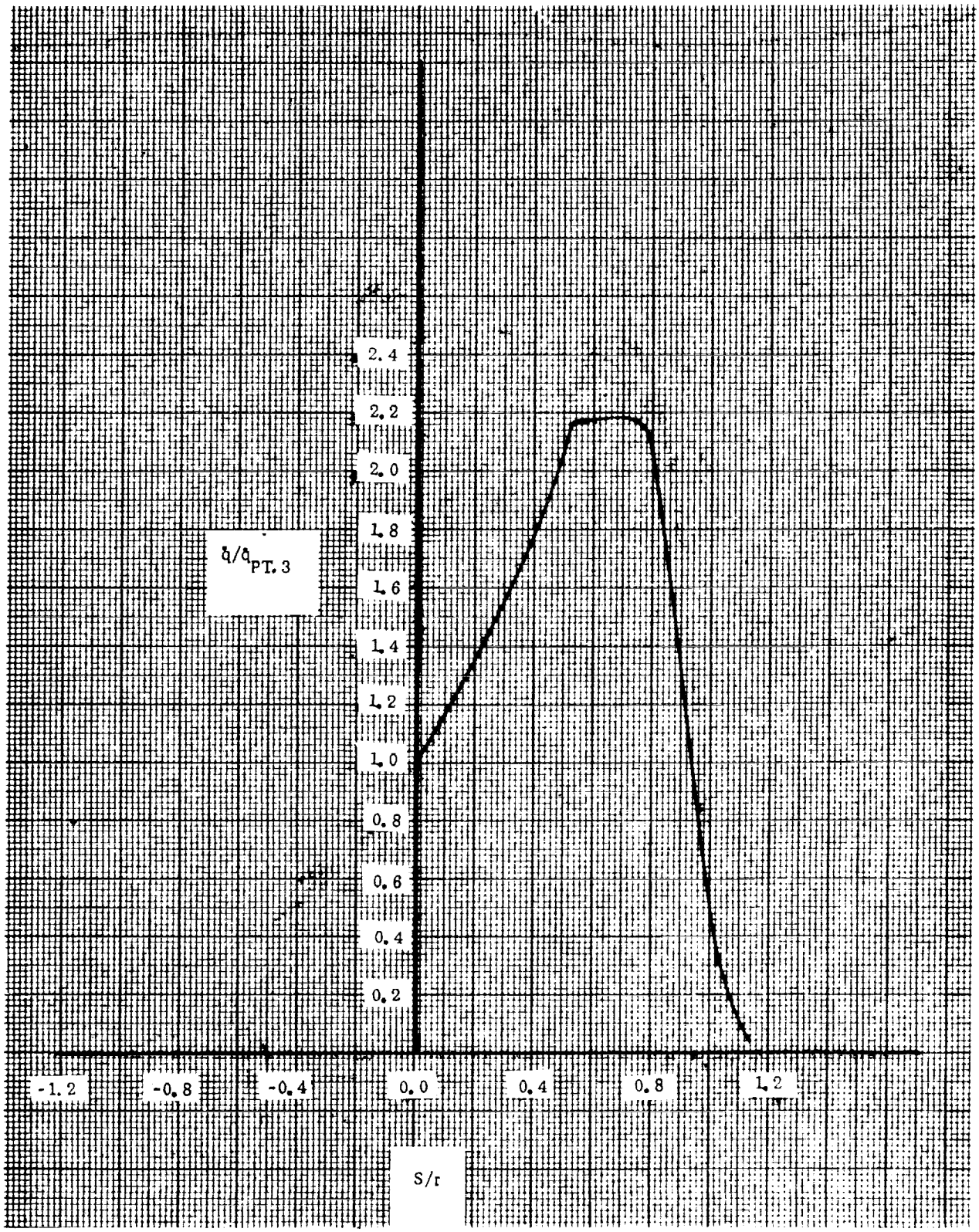

Figure 58. Trajectory HSE-4A, Equilibrium Radiation Distribution, λ = 22.5°

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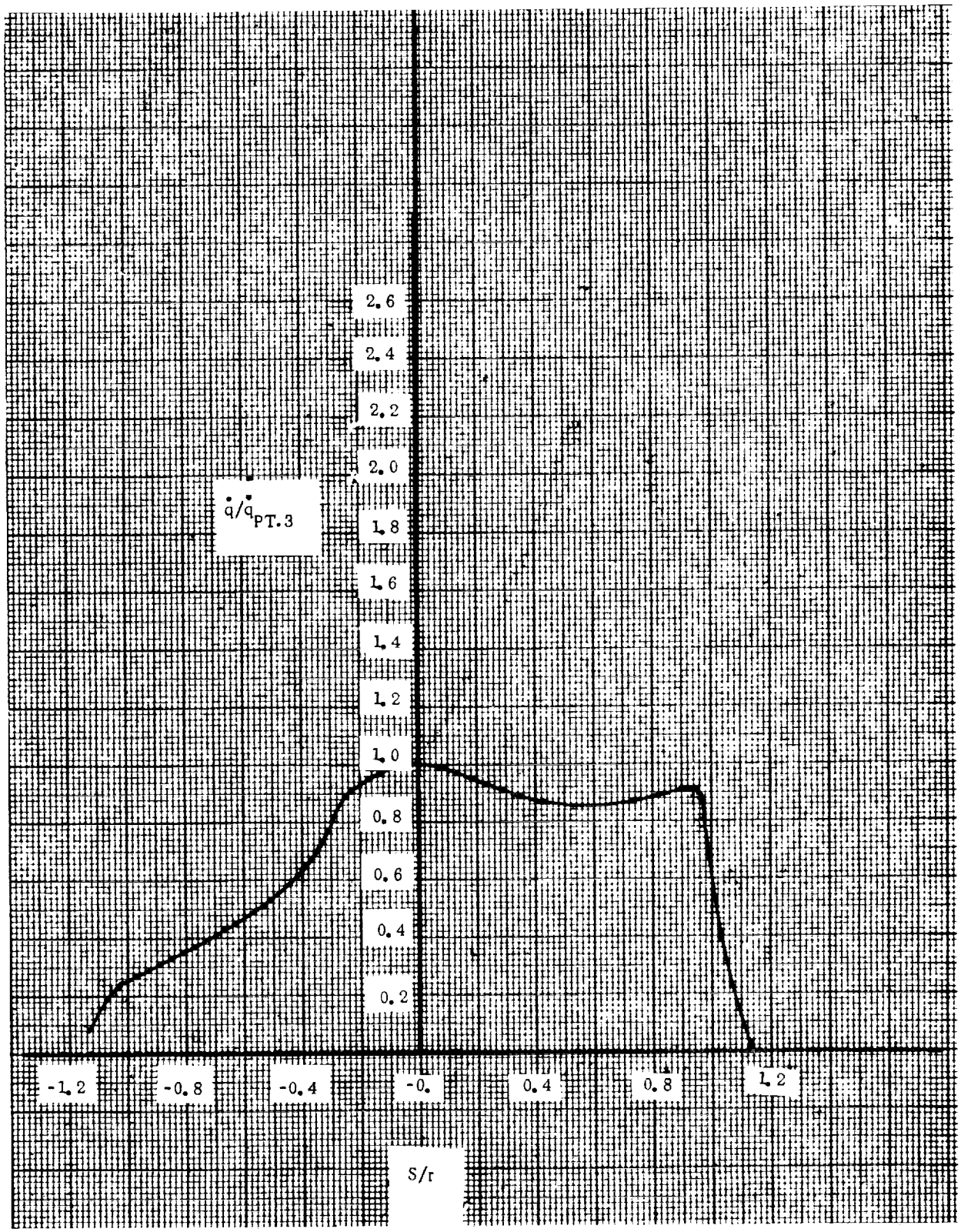

Figure 59. Trajectory HSE-4A, Equilibrium Radiation Distribution, $\lambda = 45°$

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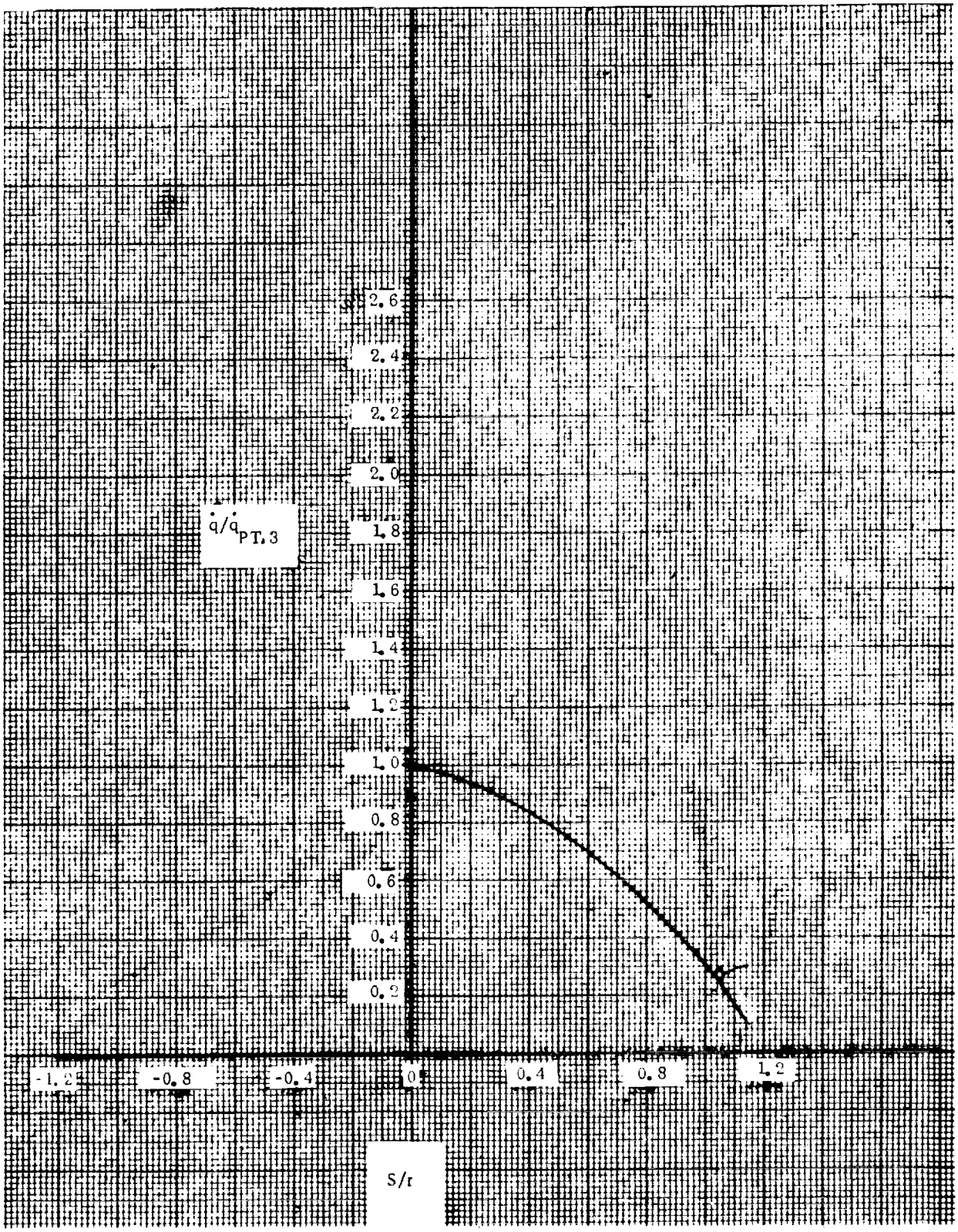

Figure 60. Trajectory HSE-4A, Equilibrium Radiation Distribution, $\lambda = 90°$

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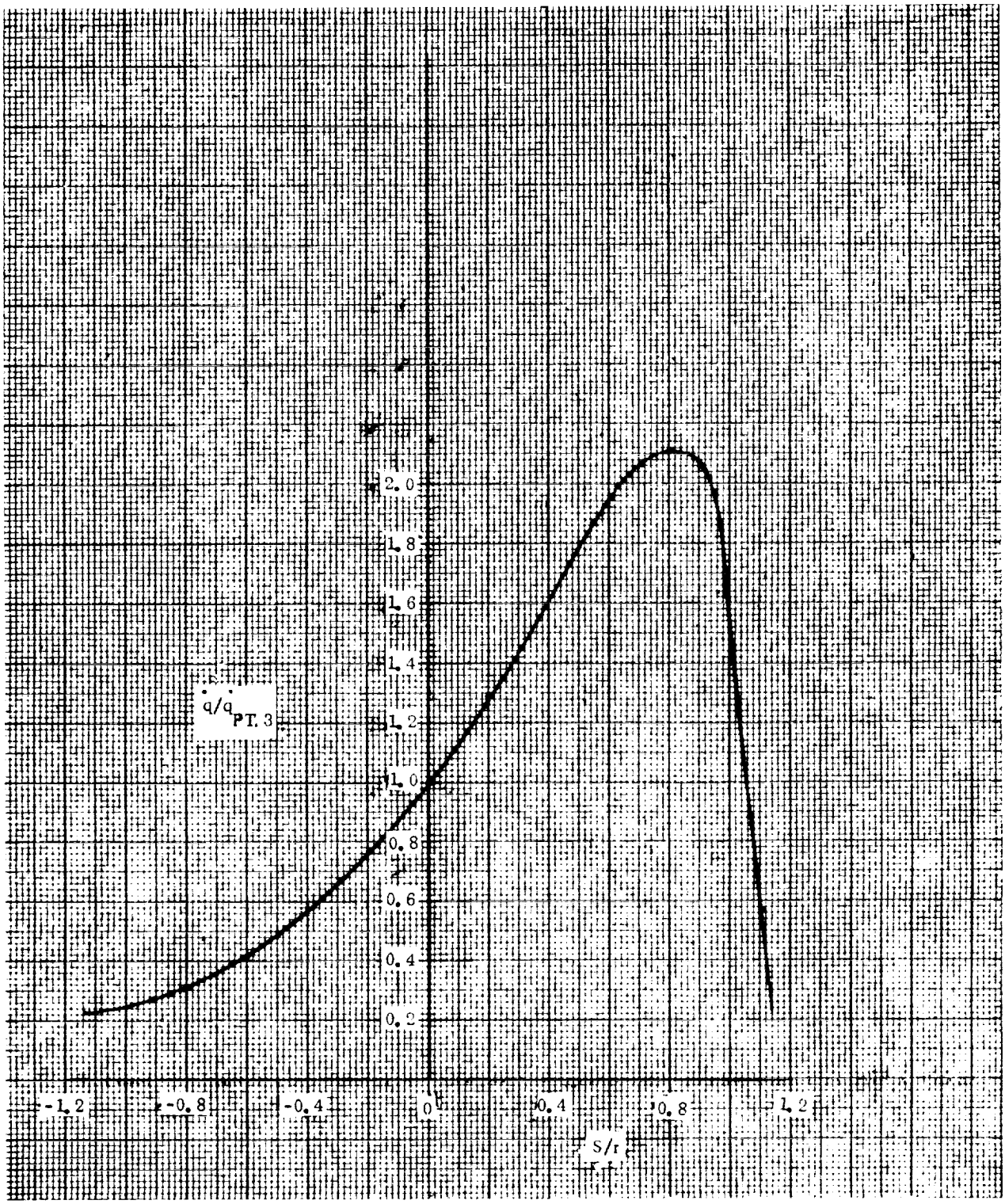

Figure 61. Trajectory HSE-4A, Non-Equilibrium Radiation Distribution, $\lambda = 0°$

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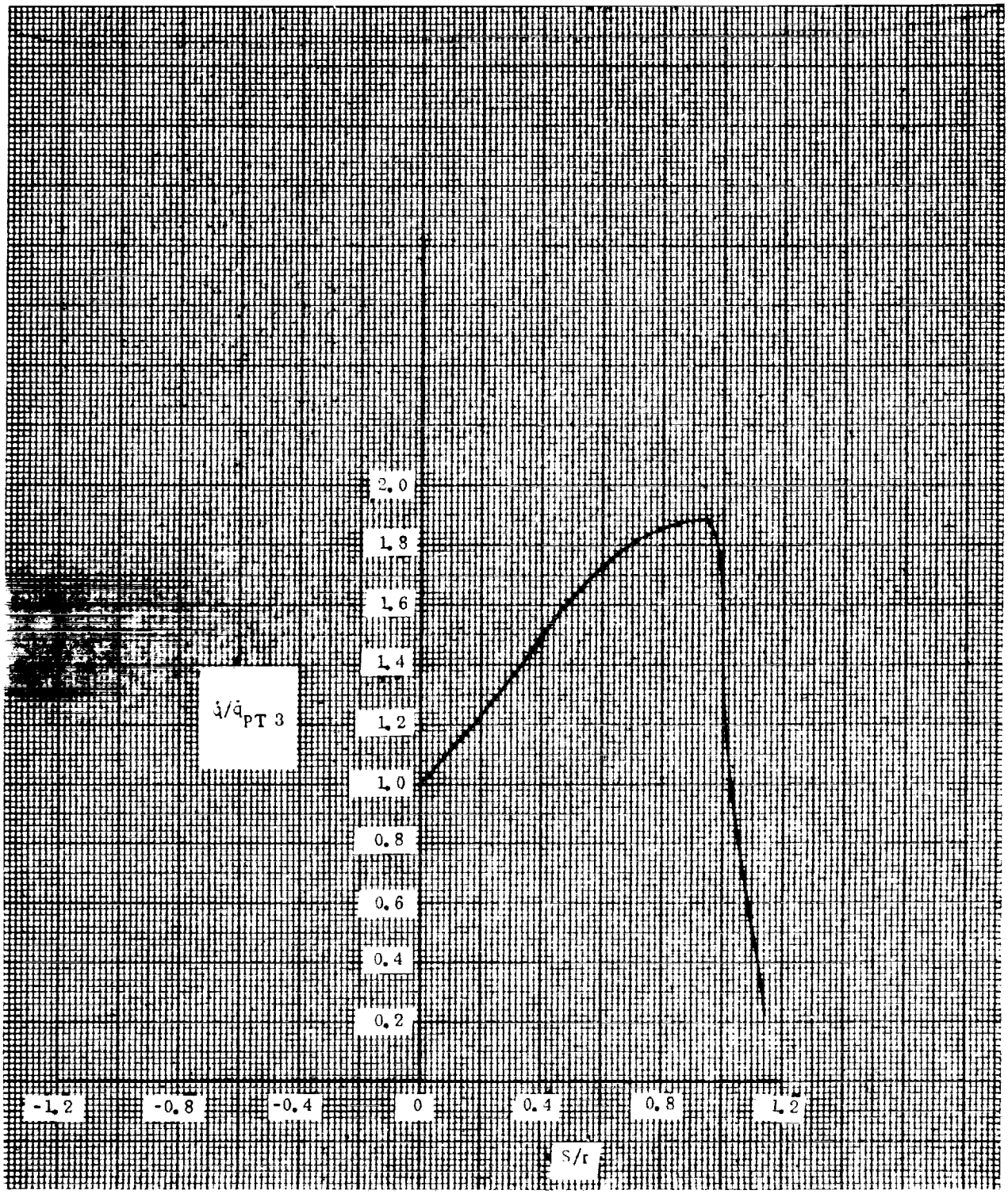

Figure 62. Trajectory HSE-4A, Non-Equilibrium Radiation Distribution, $\lambda = 22.5°$

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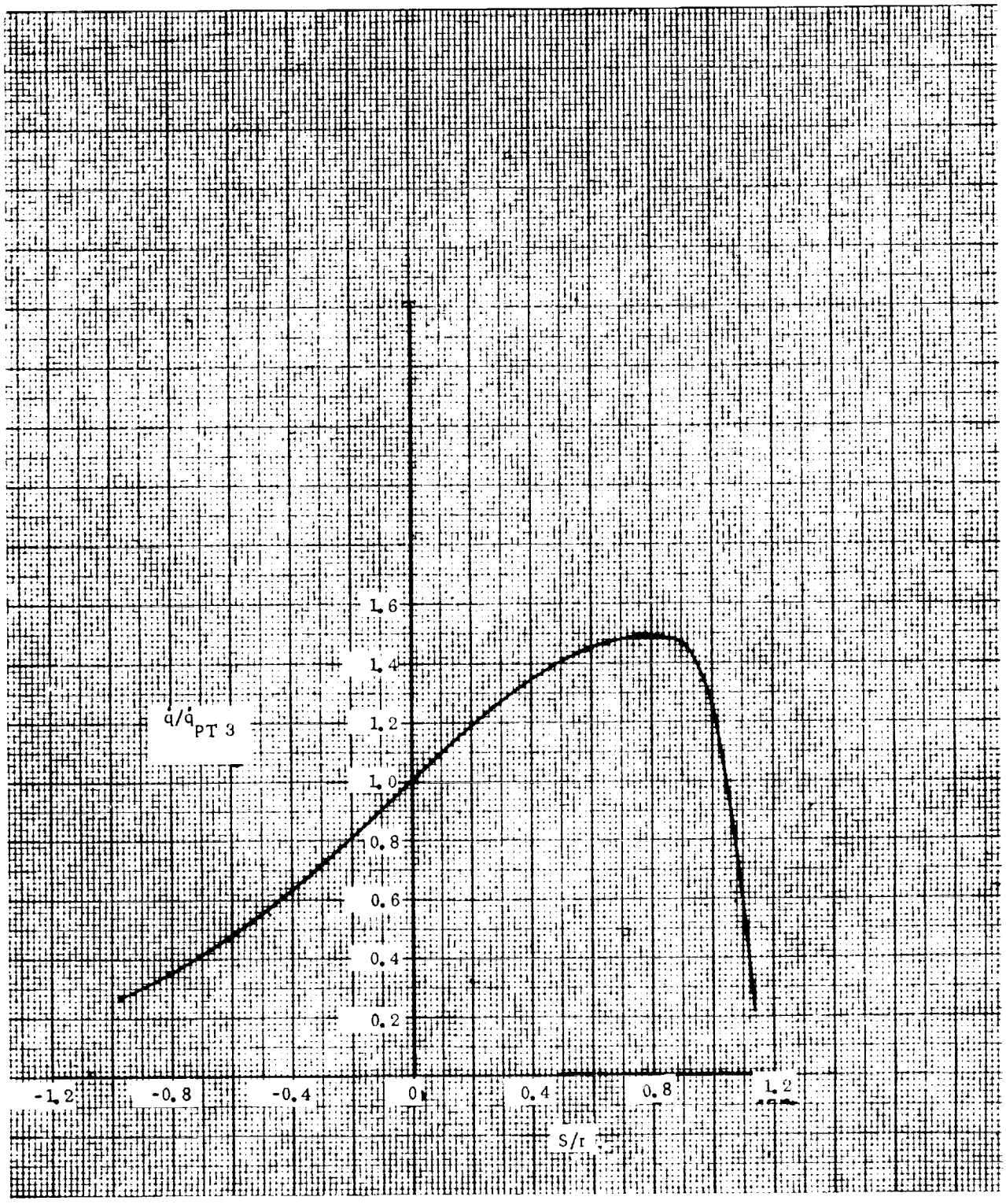

Figure 63. Trajectory HSE-4A, Non-Equilibrium Radiation Distribution, $\lambda = 45°$

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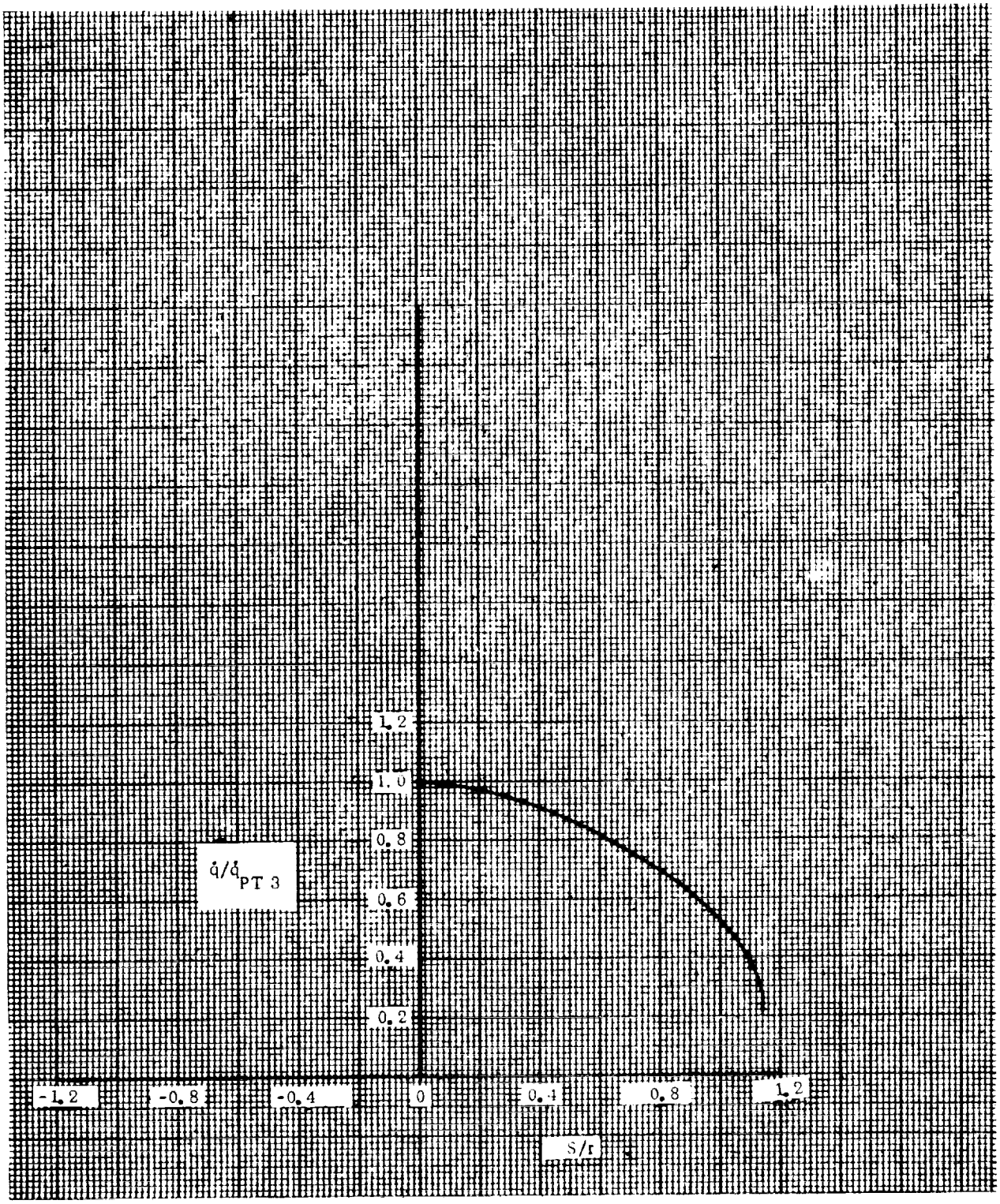

Figure 64. Trajectory HSE-4A, Non-Equilibrium Radiation Distribution, $\lambda = 90°$

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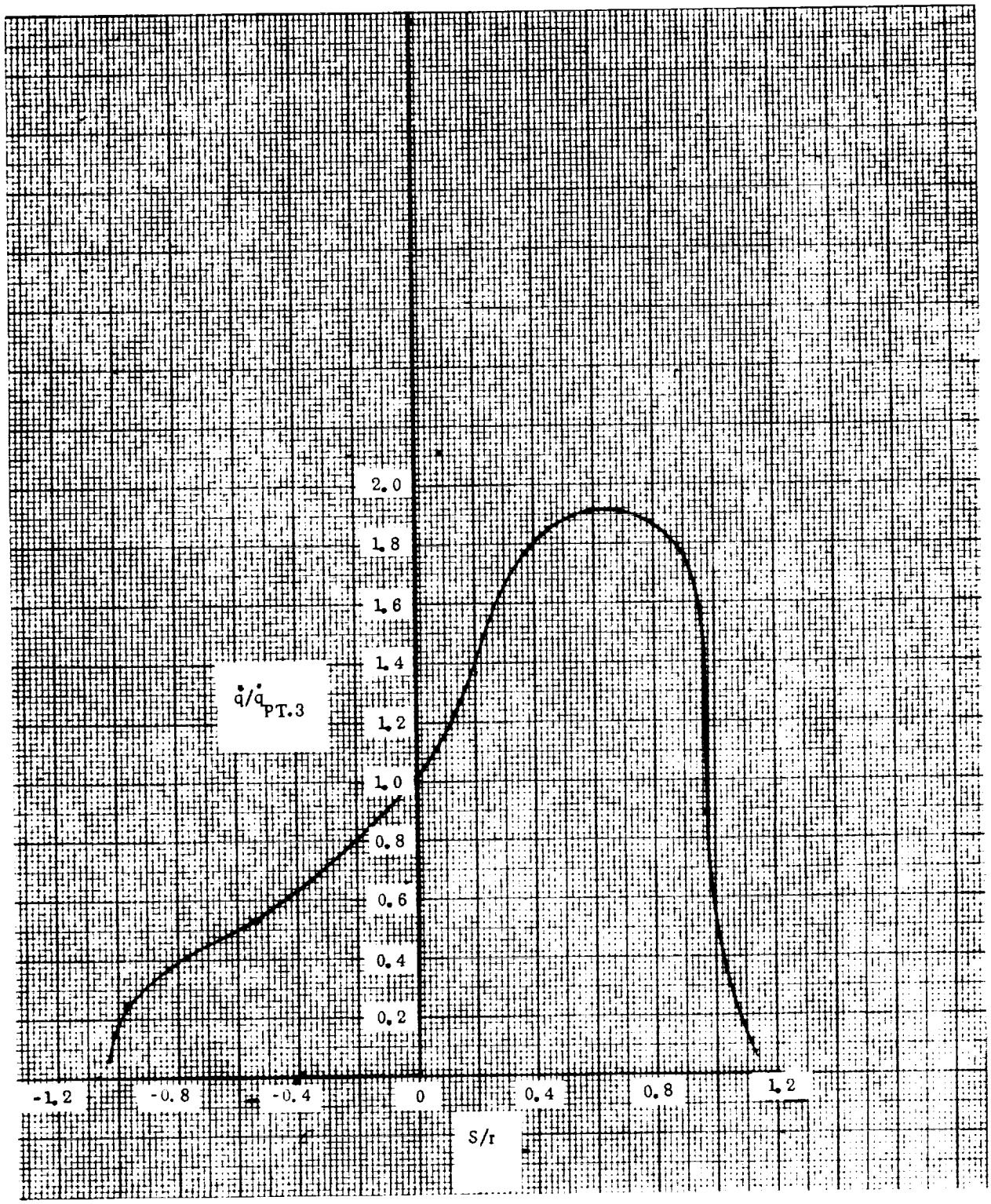

Figure 65. Trajectory HSE-6, Equilibrium Radiation Distribution, $\lambda = 0°$

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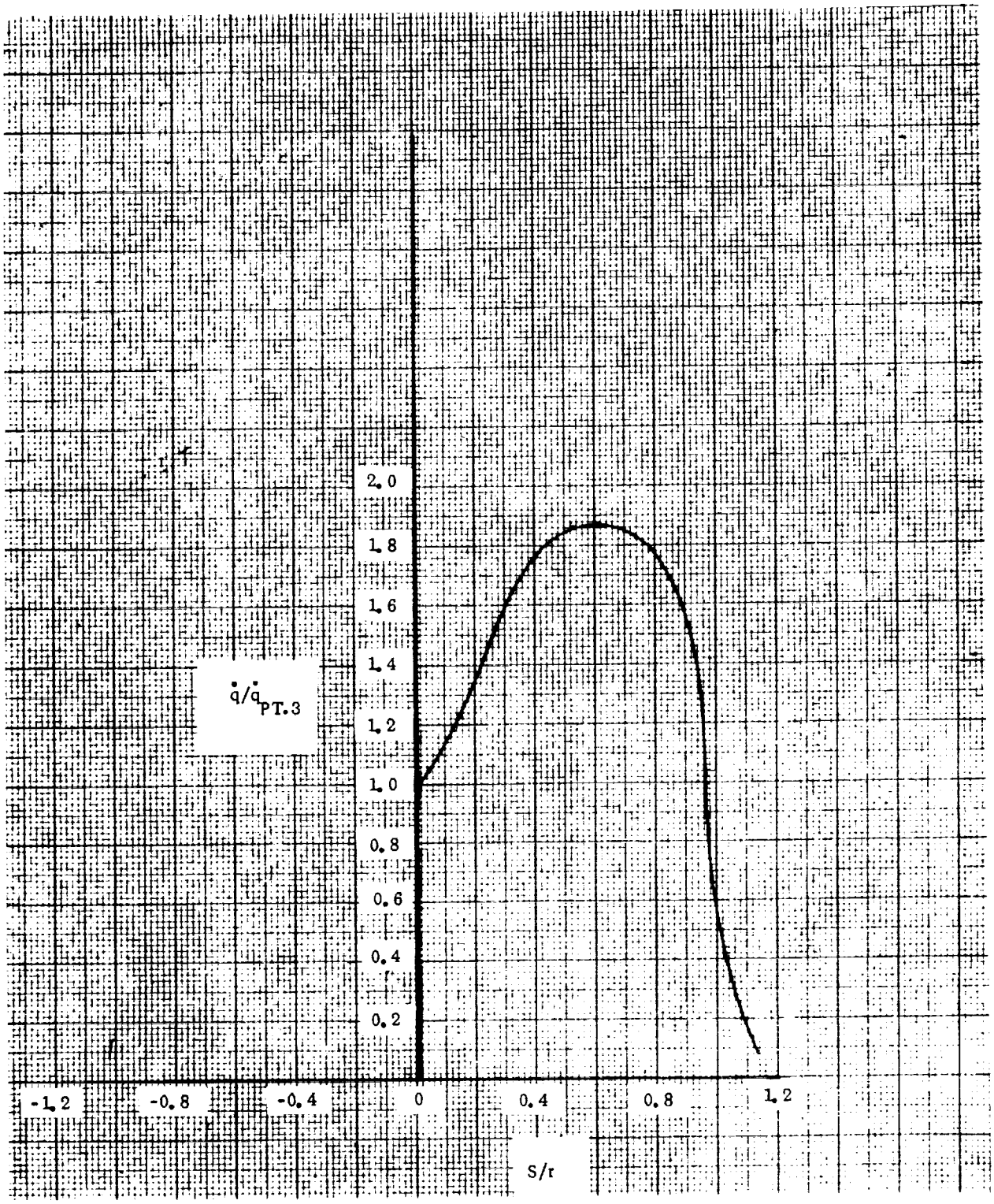

Figure 66. Trajectory HSE-6, Equilibrium Radiation Distribution, $\lambda = 22.5°$

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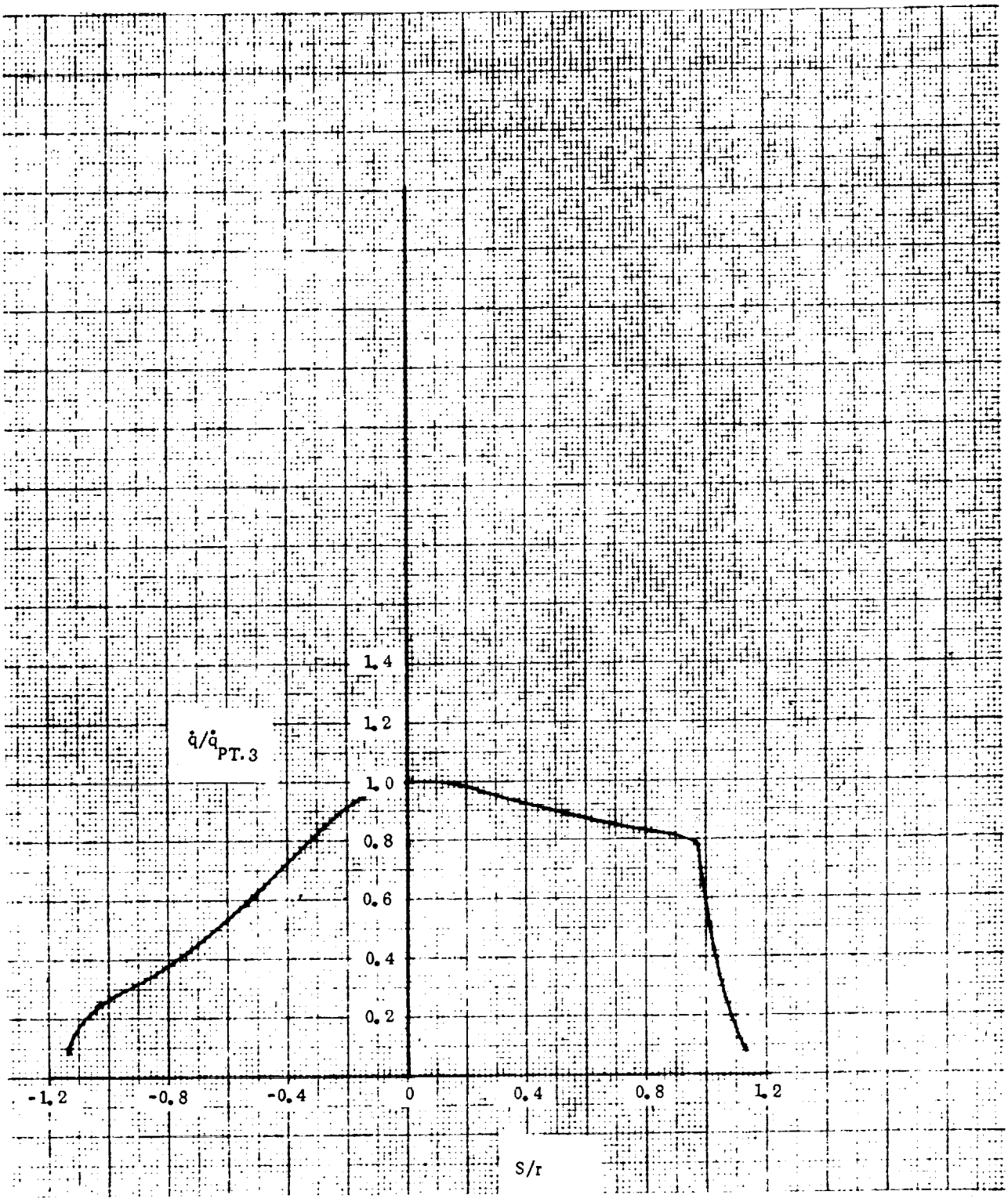

Figure 67. Trajectory HSE-6, Equilibrium Radiation Distribution, $\lambda = 45°$

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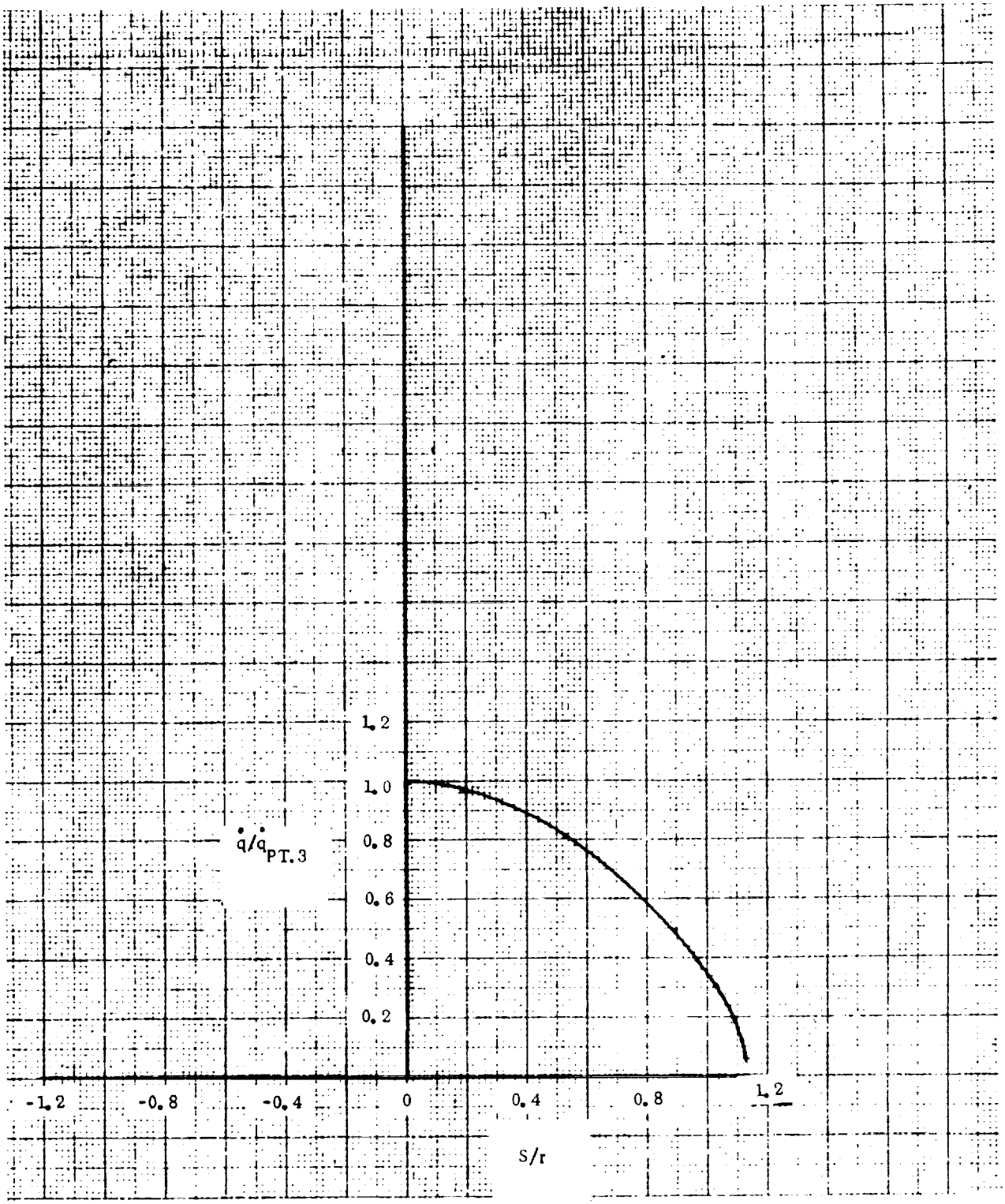

Figure 68. Trajectory HSE-6, Equilibrium Radiation Distribution, $\lambda = 90°$

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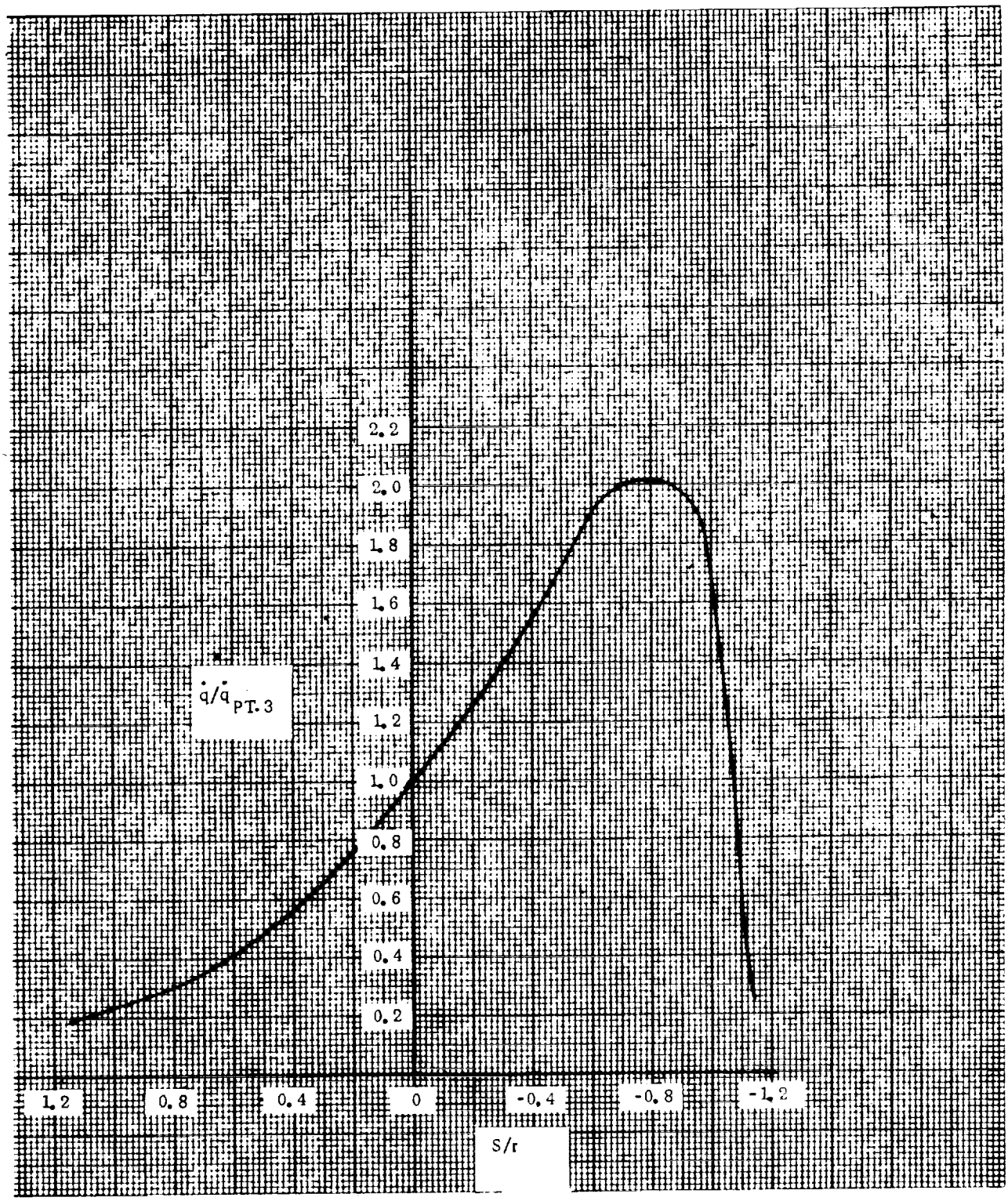

Figure 69. Trajectory HSE-6, Non-Equilibrium Radiation Distribution, $\lambda = 0°$

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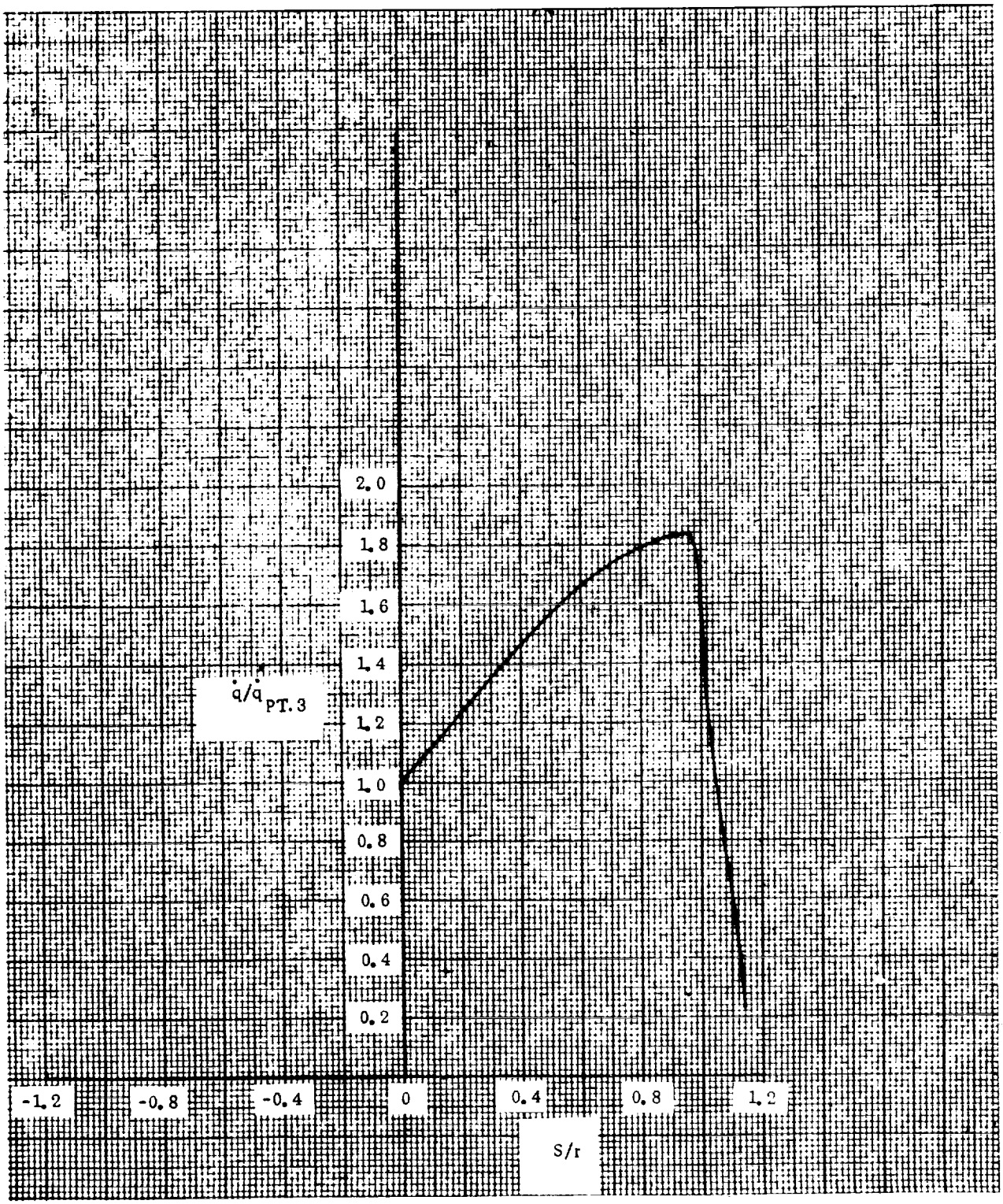

Figure 70. Trajectory HSE-6, Non-Equilibrium Radiation Distribution, $\lambda = 22.5°$

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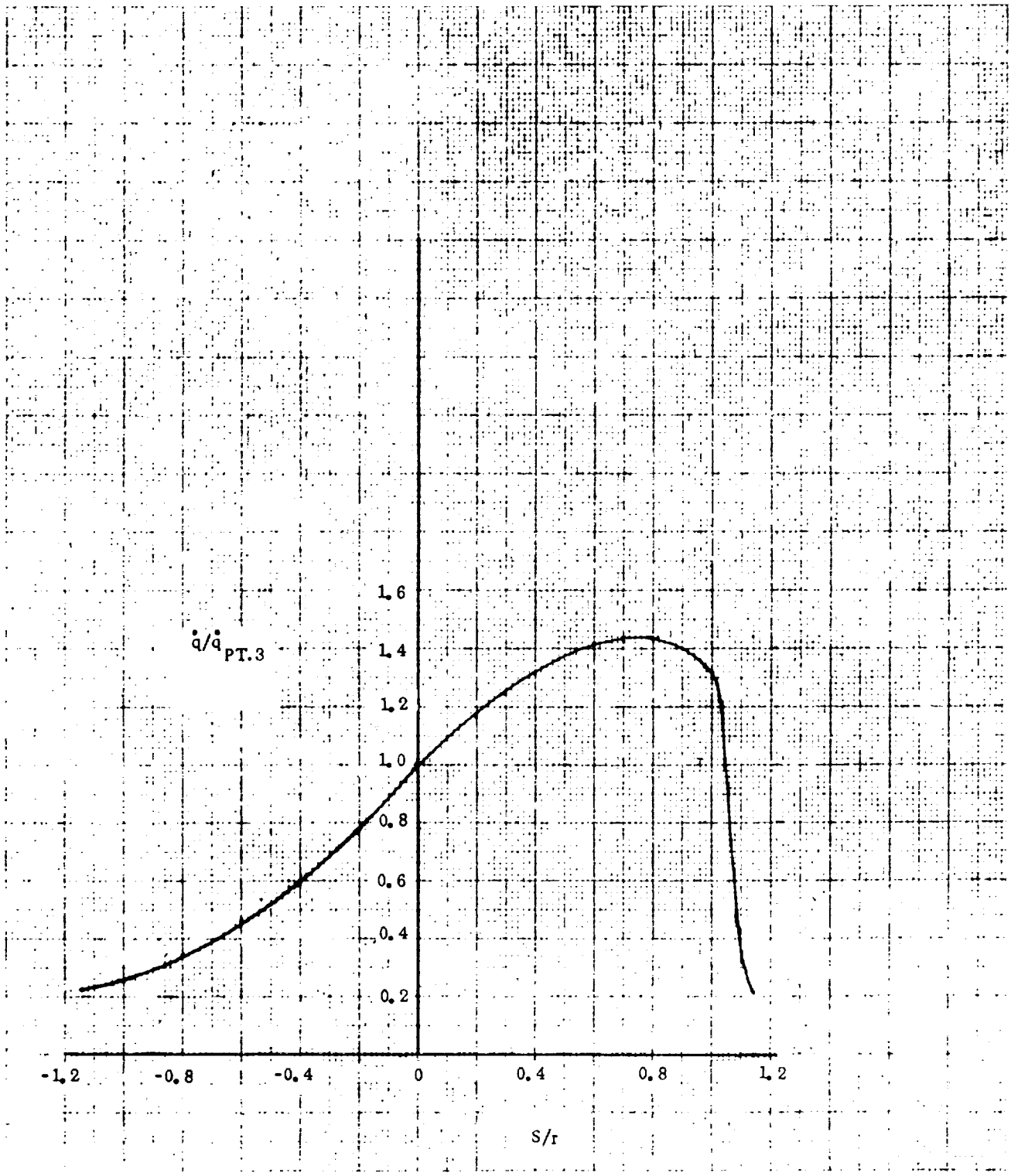

Figure 71. Trajectory HSE-6, Non-Equilibrium Radiation Distribution, $\lambda = 45°$

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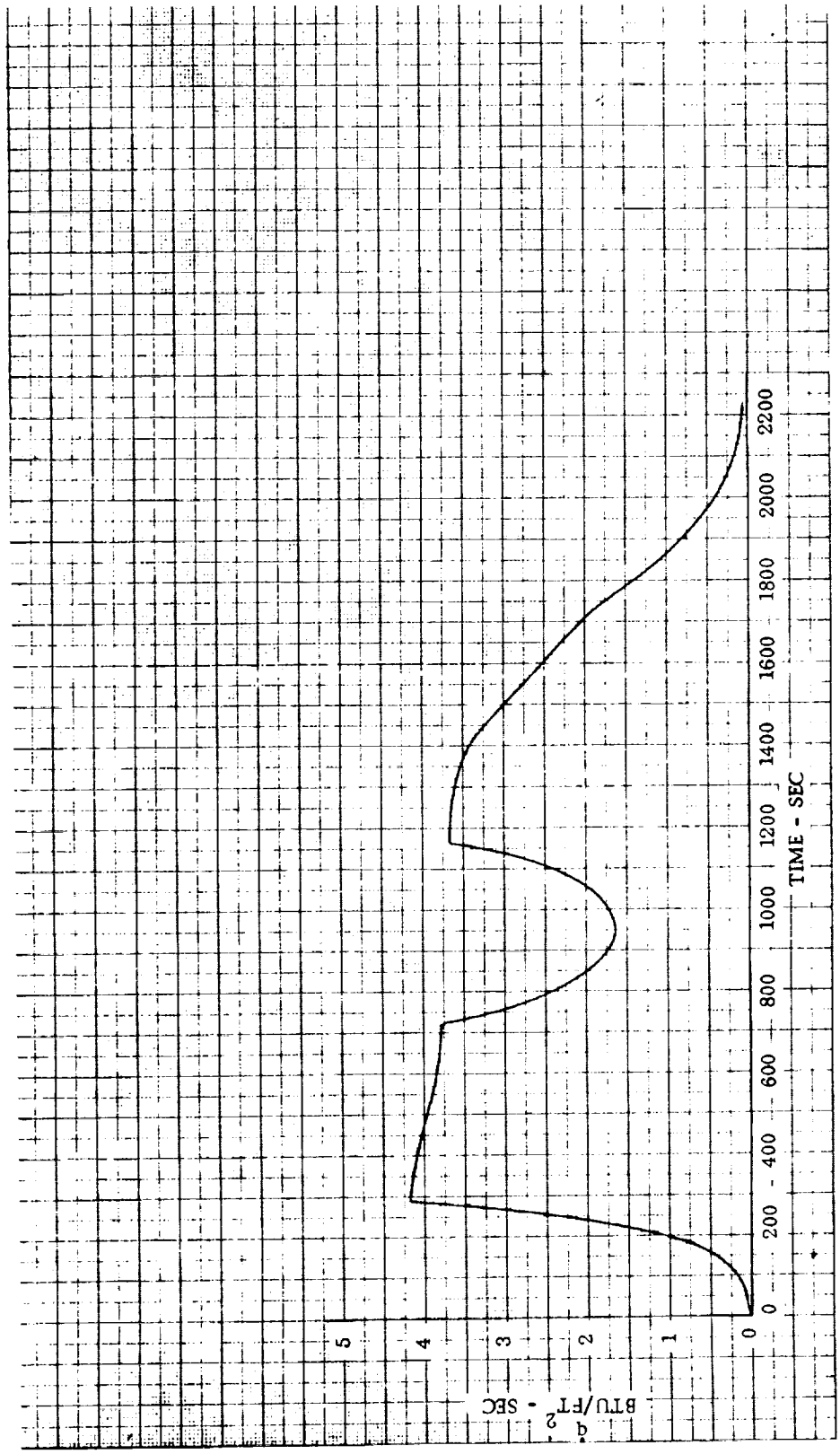

Figure 73. Trajectory HSE-1, Body Point 3, Non-Equilibrium Radiation

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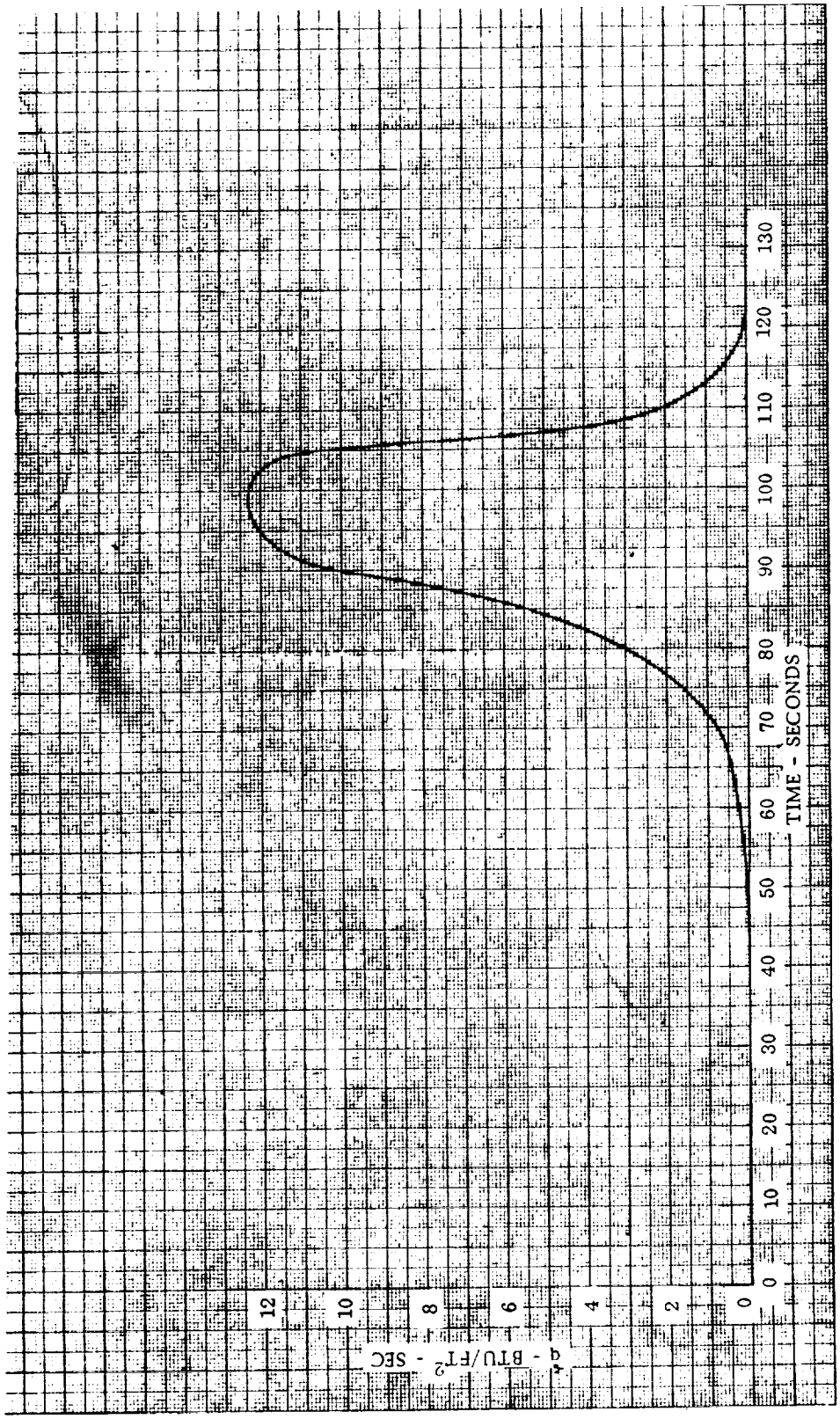

Figure 74. Trajectory HSE-2, Body Point 3, Equilibrium Radiation

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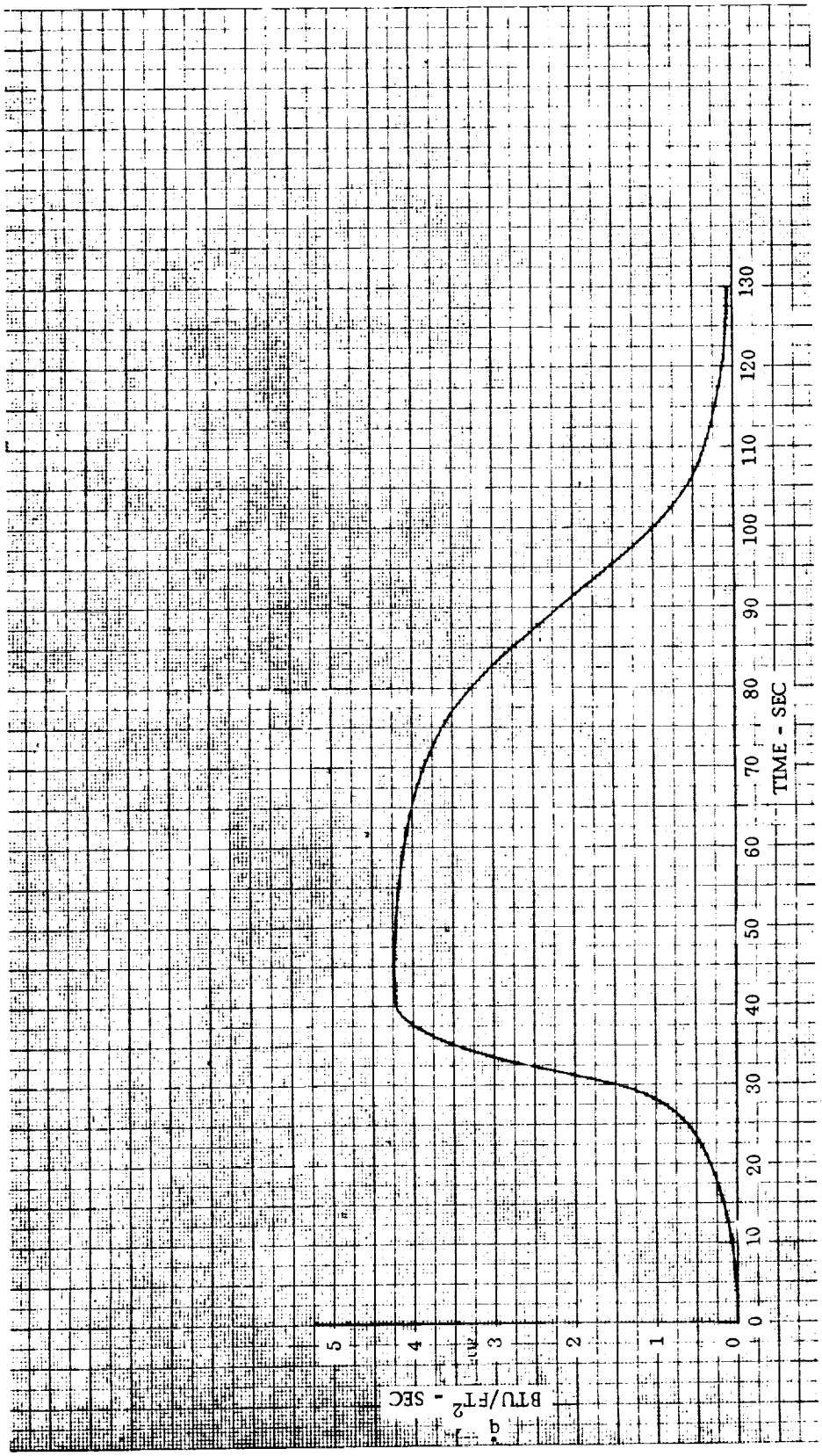

Figure 75. Trajectory HSE-2, Body Point 3, Non-Equilibrium Radiation

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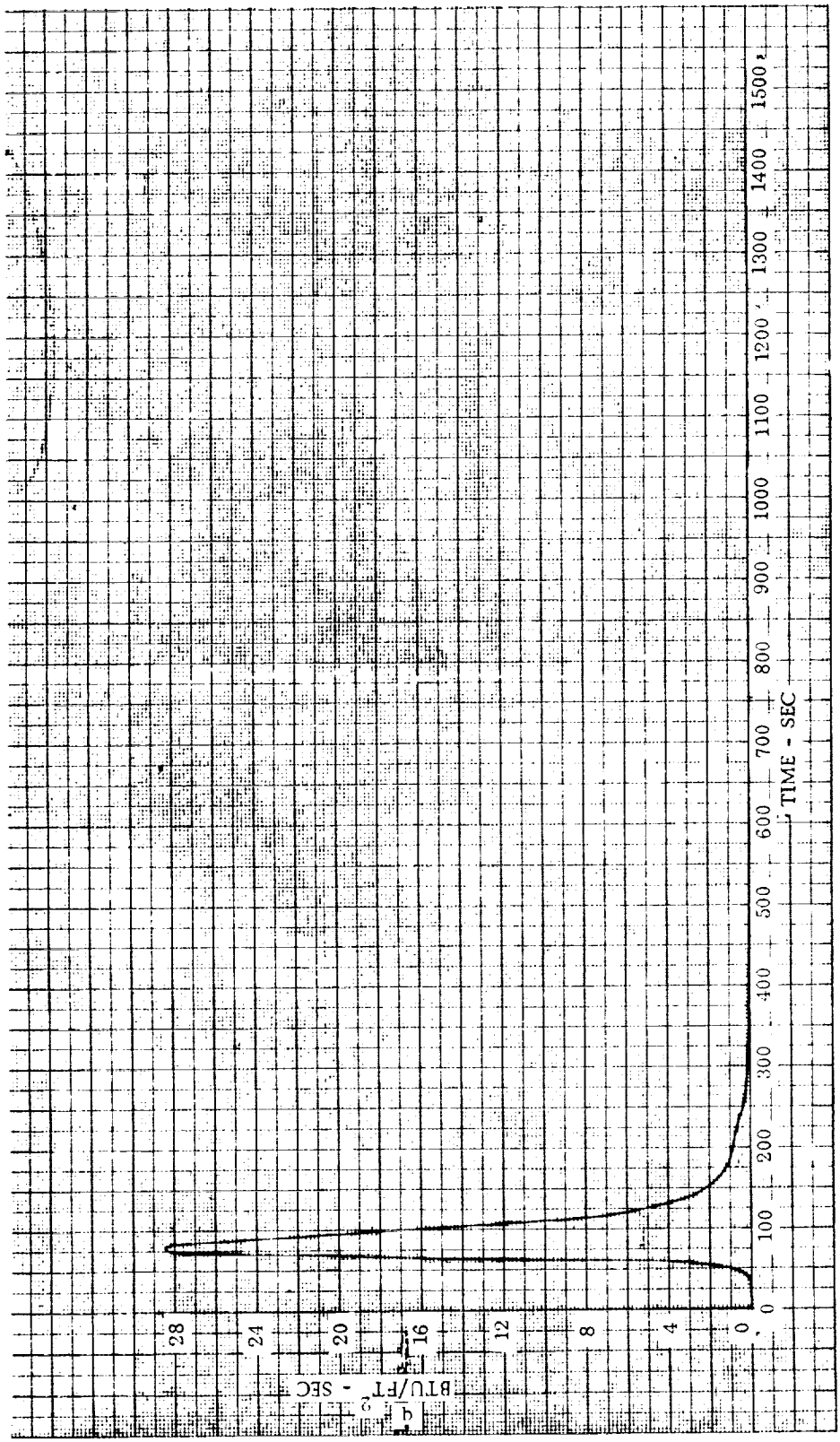

Figure 76. Trajectory HSE-3A, Body Point 3, Equilibrium Radiation

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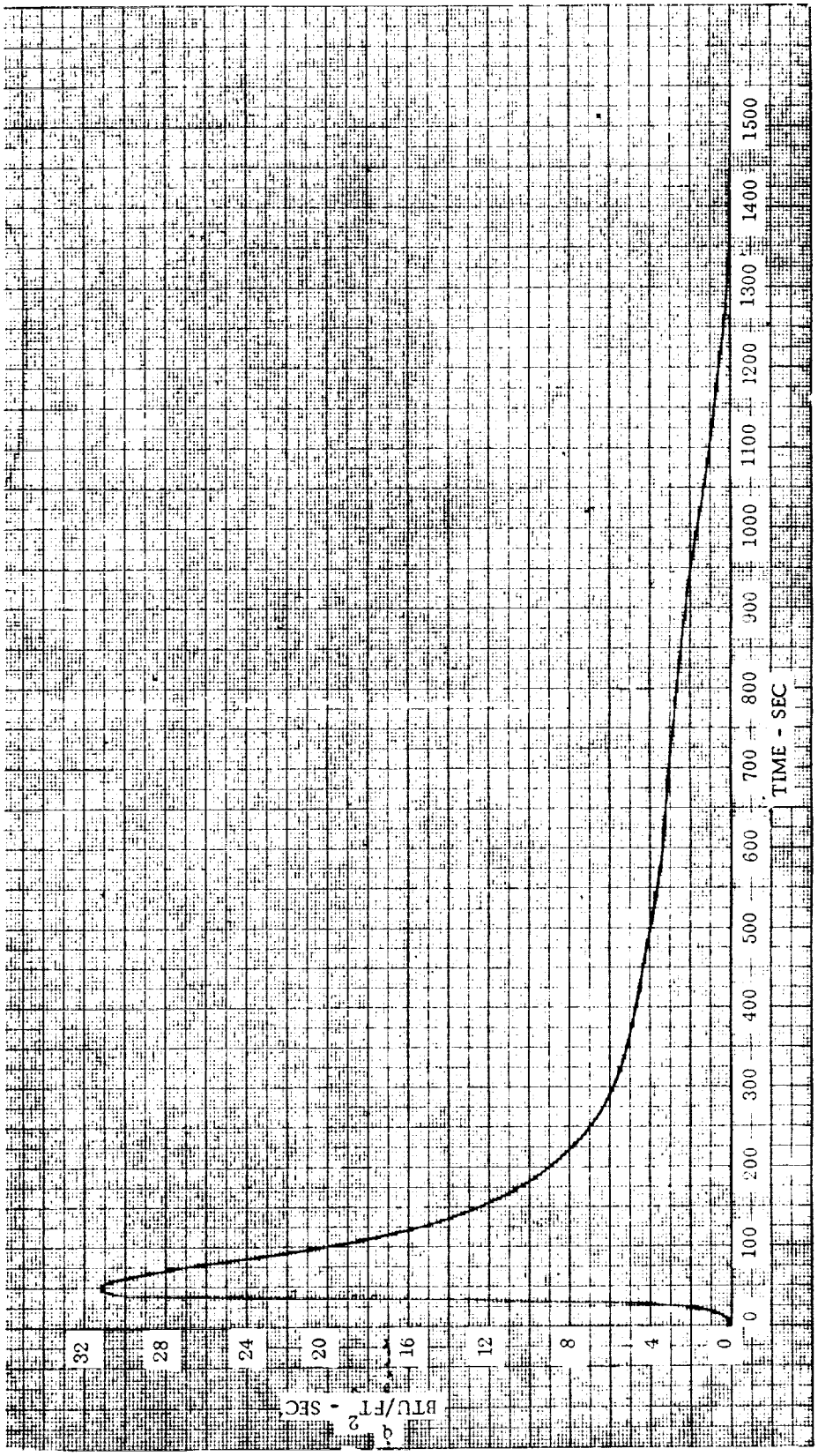

Figure 77. Trajectory HSE-3A, Body Point 3, Non-Equilibrium Radiation

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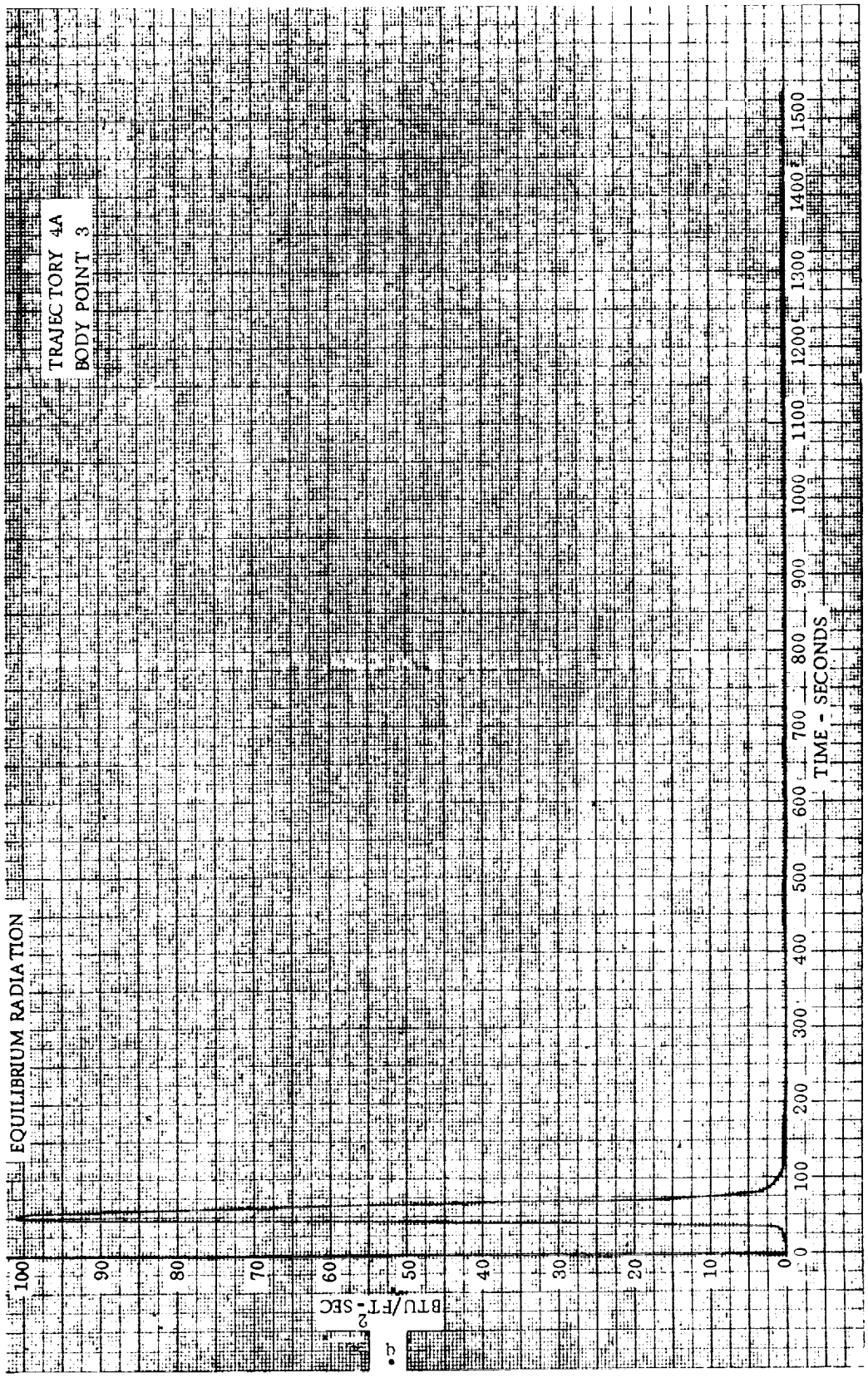

Figure 78. Trajectory HSE-4A, Body Point 3, Equilibrium Radiation

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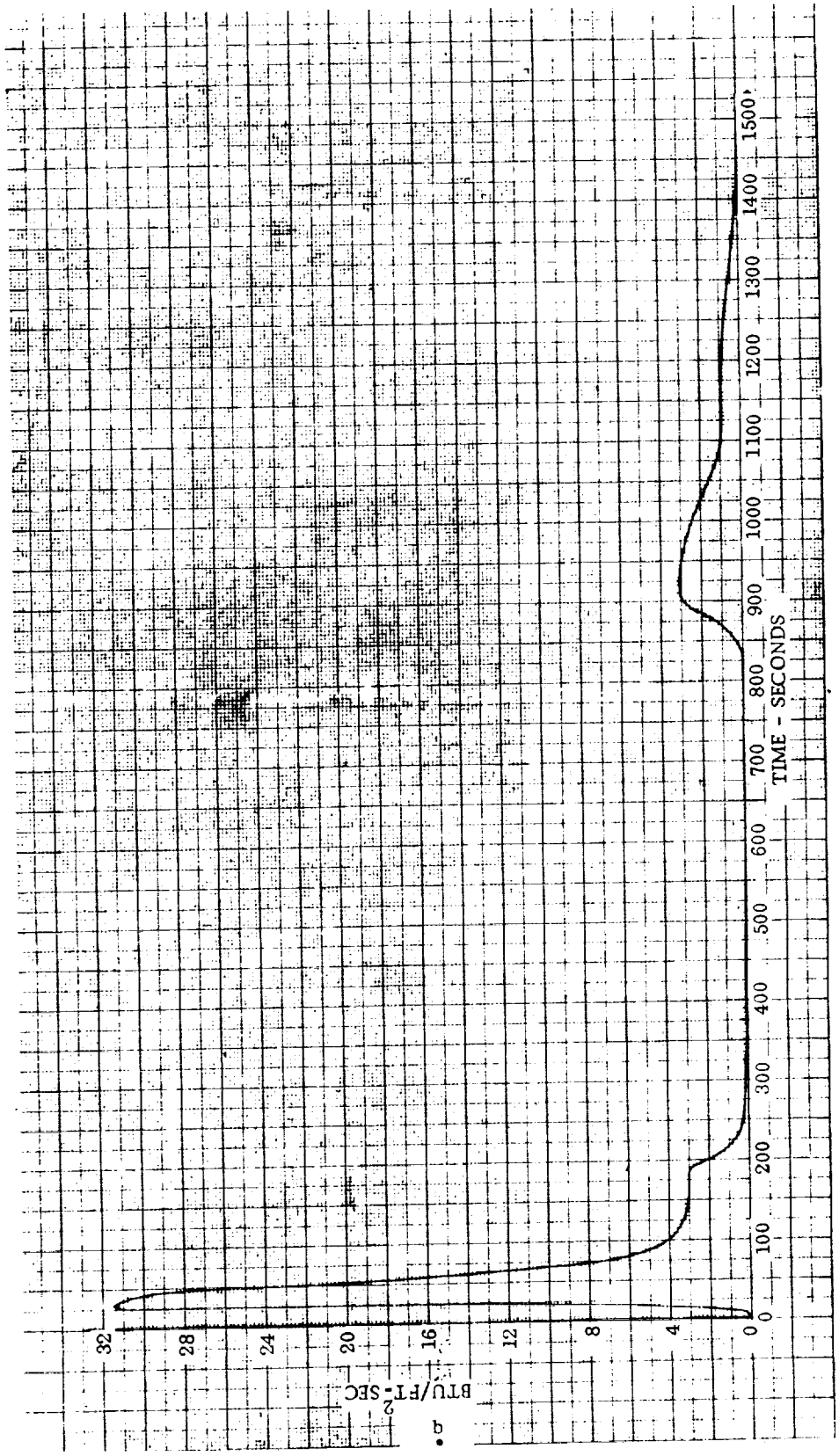

Figure 79. Trajectory HSE-4A, Body Point 3, Non-Equilibrium Radiation

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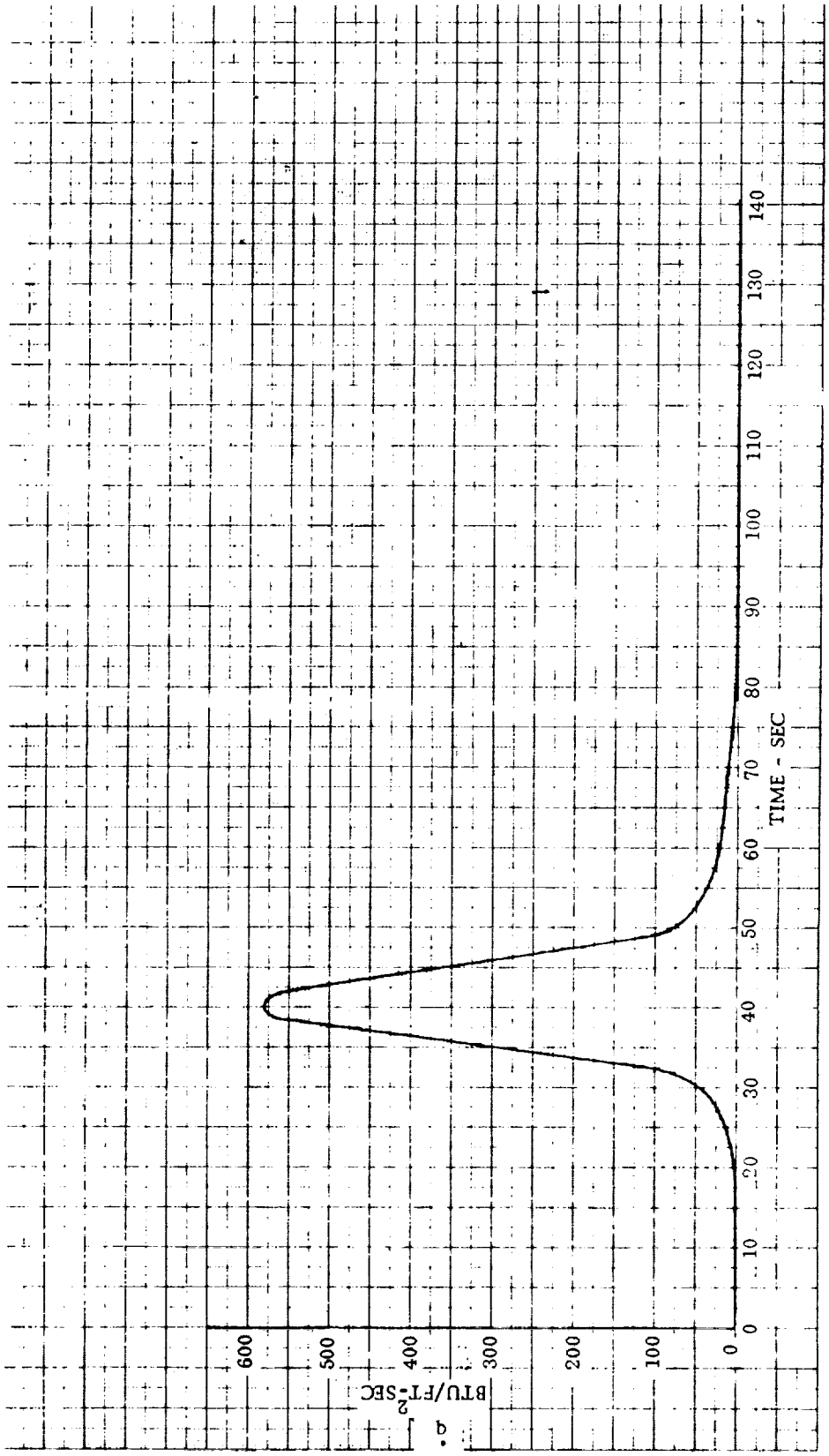

Figure 80. Trajectory HSE-6, Body Point 3, Equilibrium Radiation

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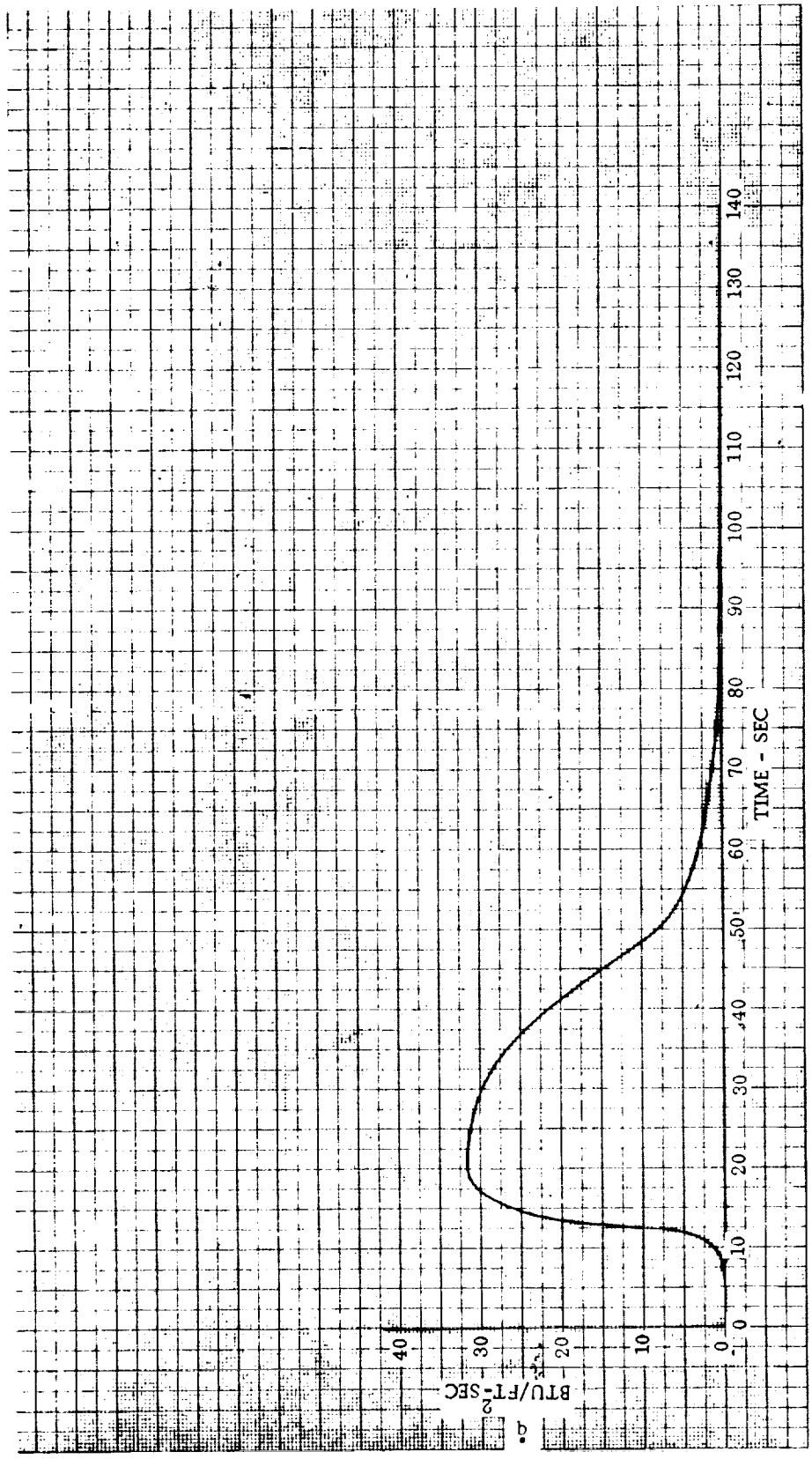

Figure 81. Trajectory HSE-6, Body Point 3, Non-Equilibrium Radiation

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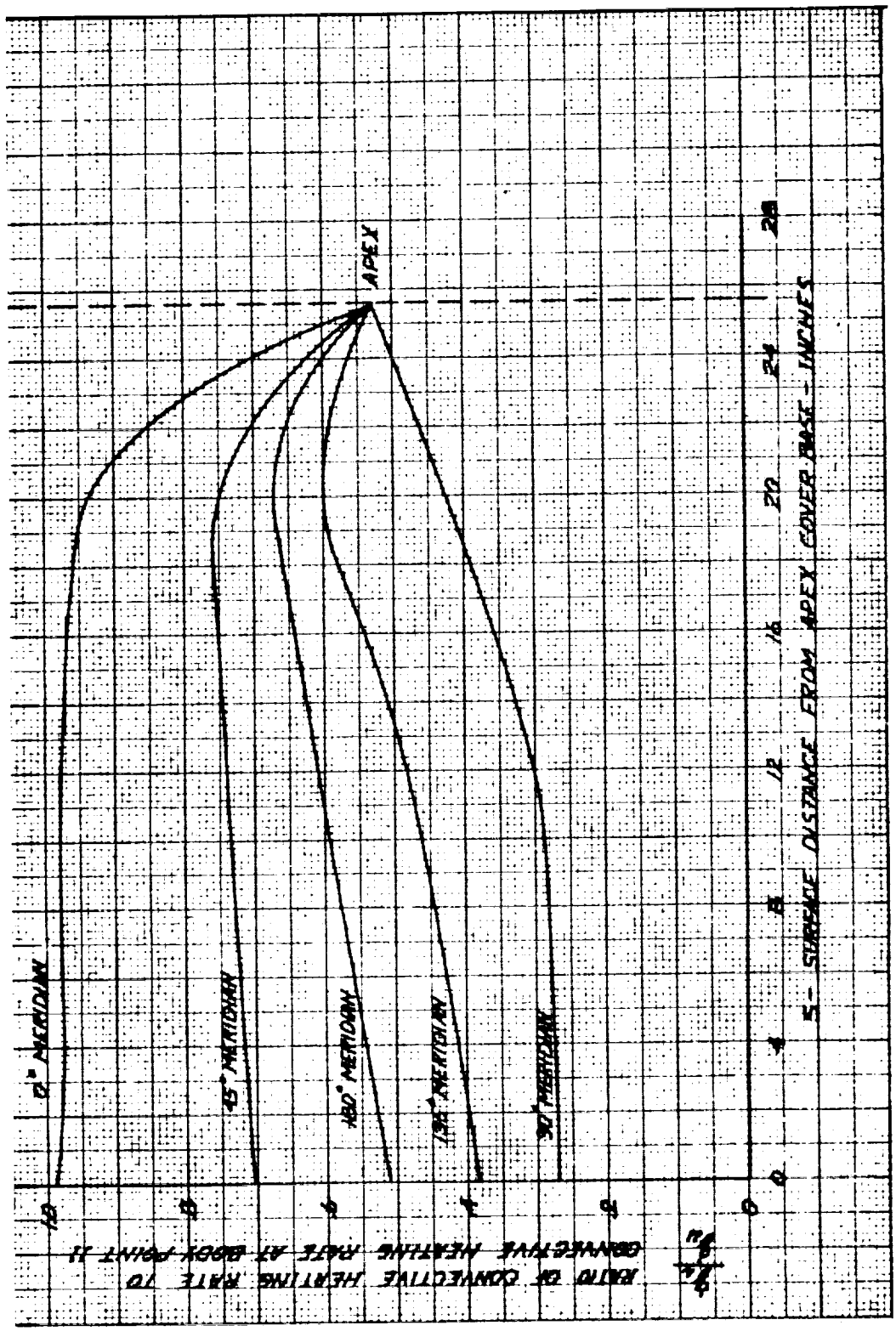

Figure 82. Entry Heating Rate Distributions on Command Module Forward Compartment Apex Cover (No Strake Effect Included)

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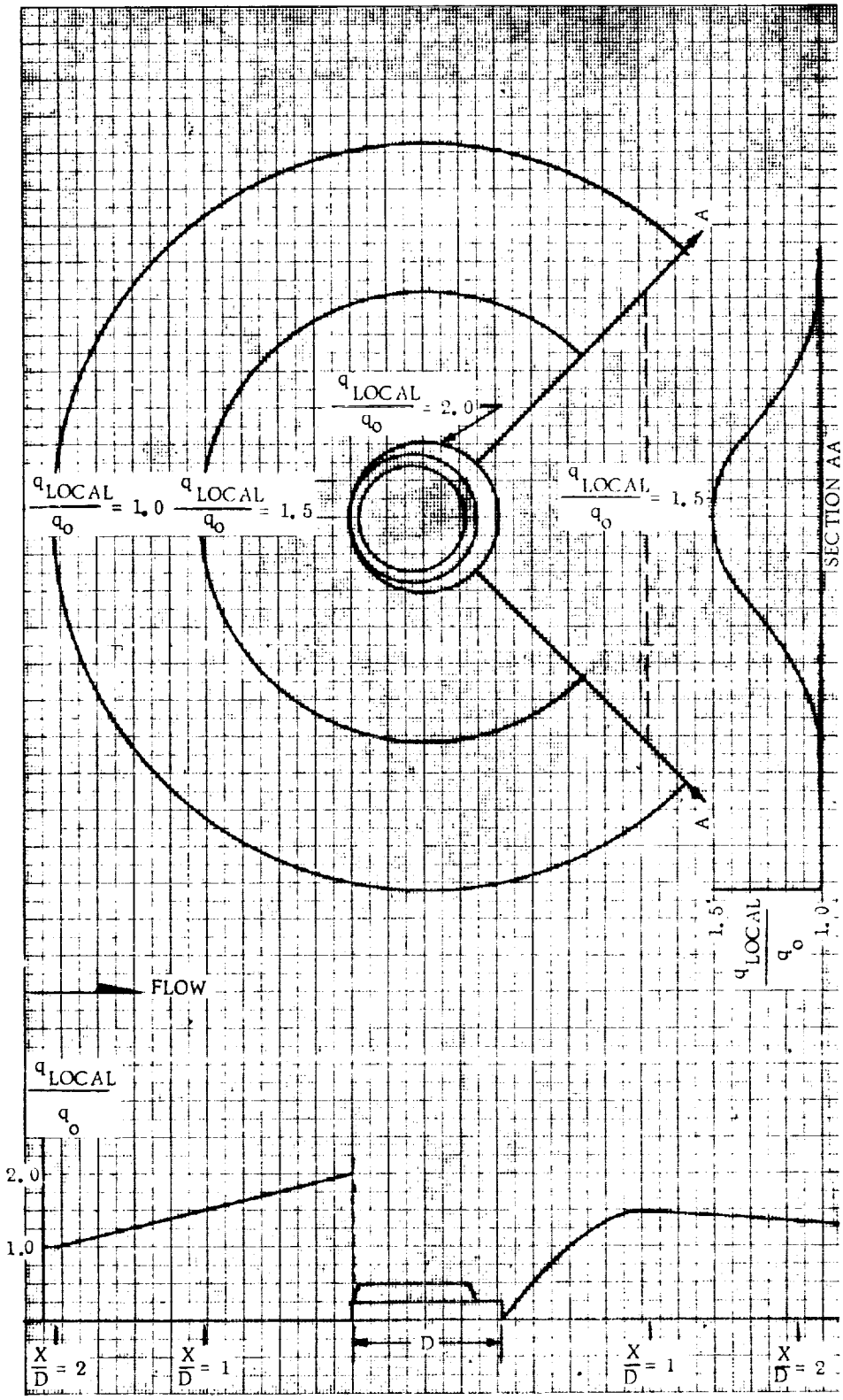

Figure 83. Heating Rate Distribution in the Vicinity of Command Module Shear Pads

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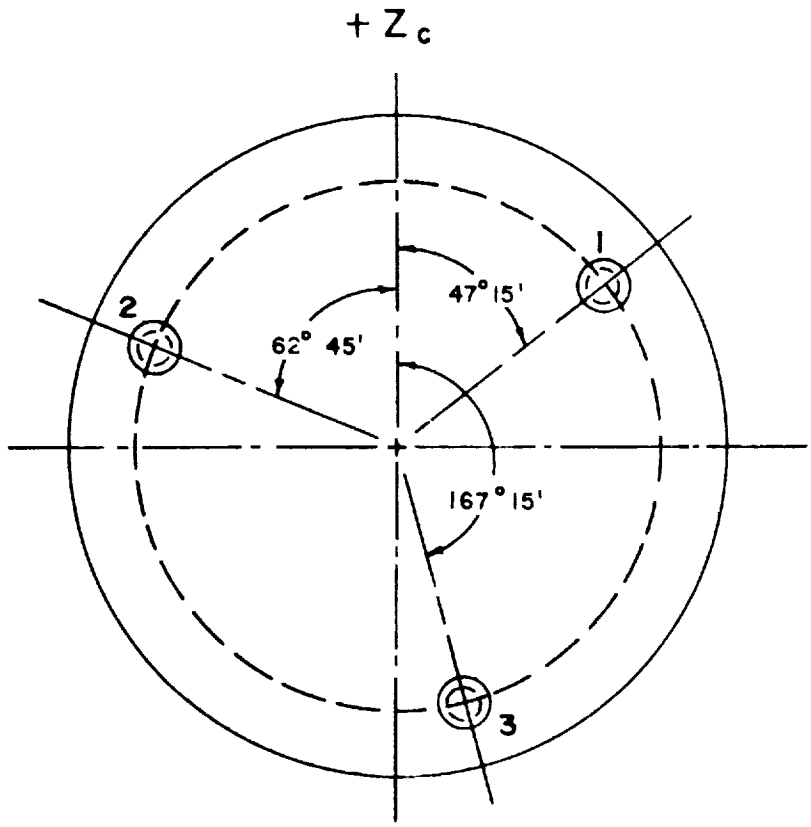

Figure 83A. Location of Shear Pads

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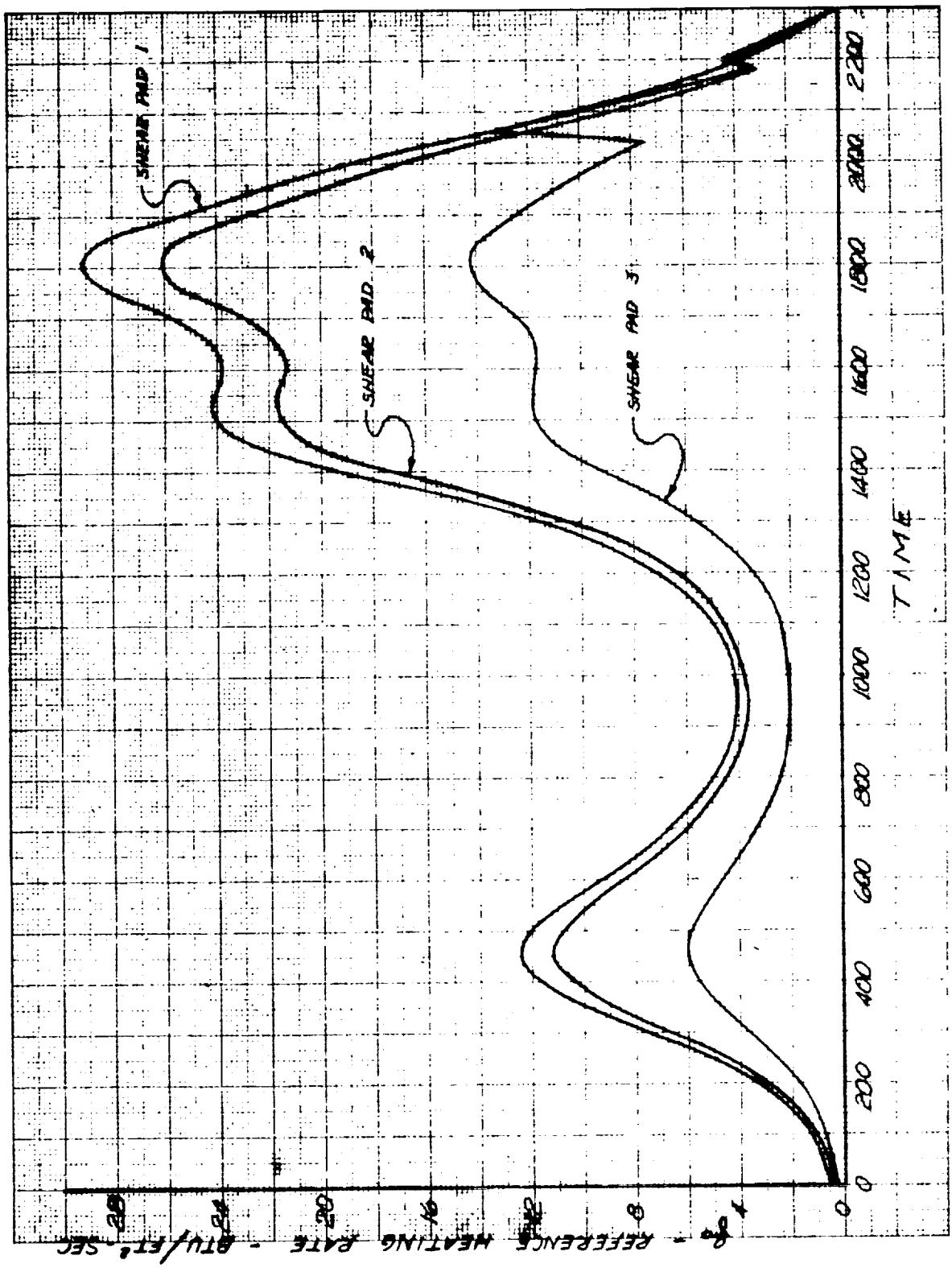

Figure 84. $\dot{q}_o$ Heating Rate Based on Trajectory HSE-1

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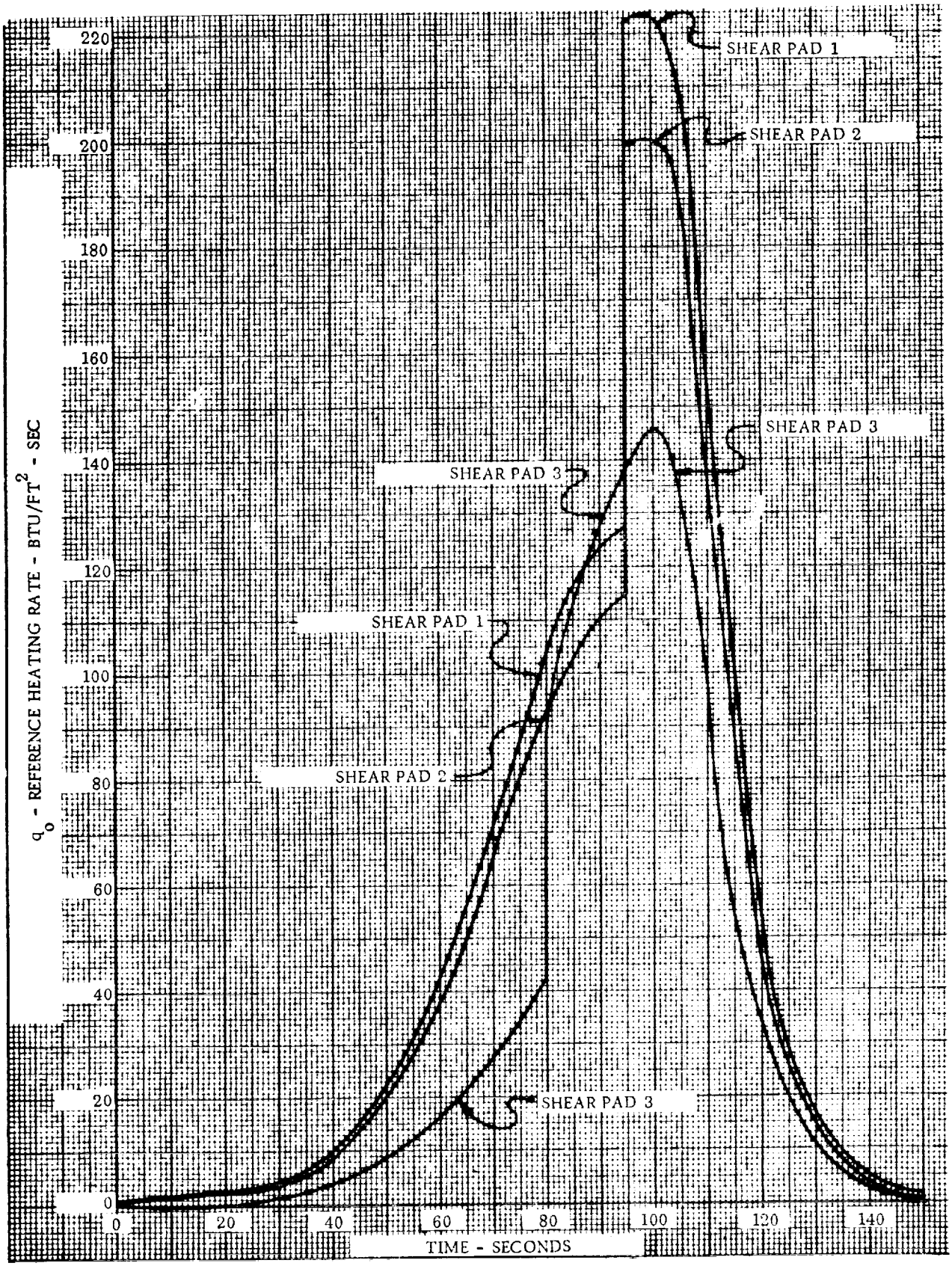

Figure 85. $\dot{q}_o$ Heating Rate Based on Trajectory HSE-2

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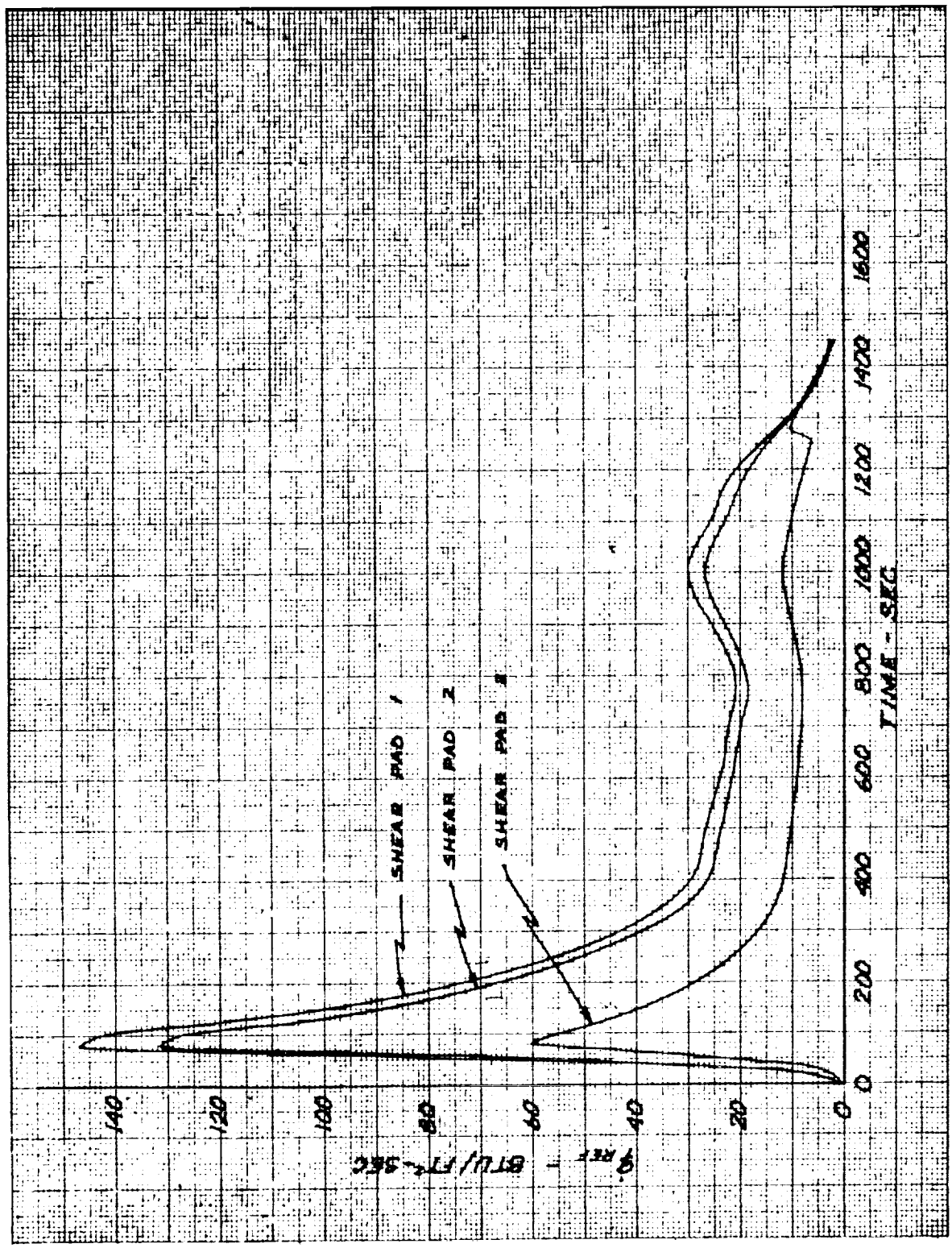

Figure 86. $\dot{q}_o$ Heating Rate Based on Trajectory HSE-3A

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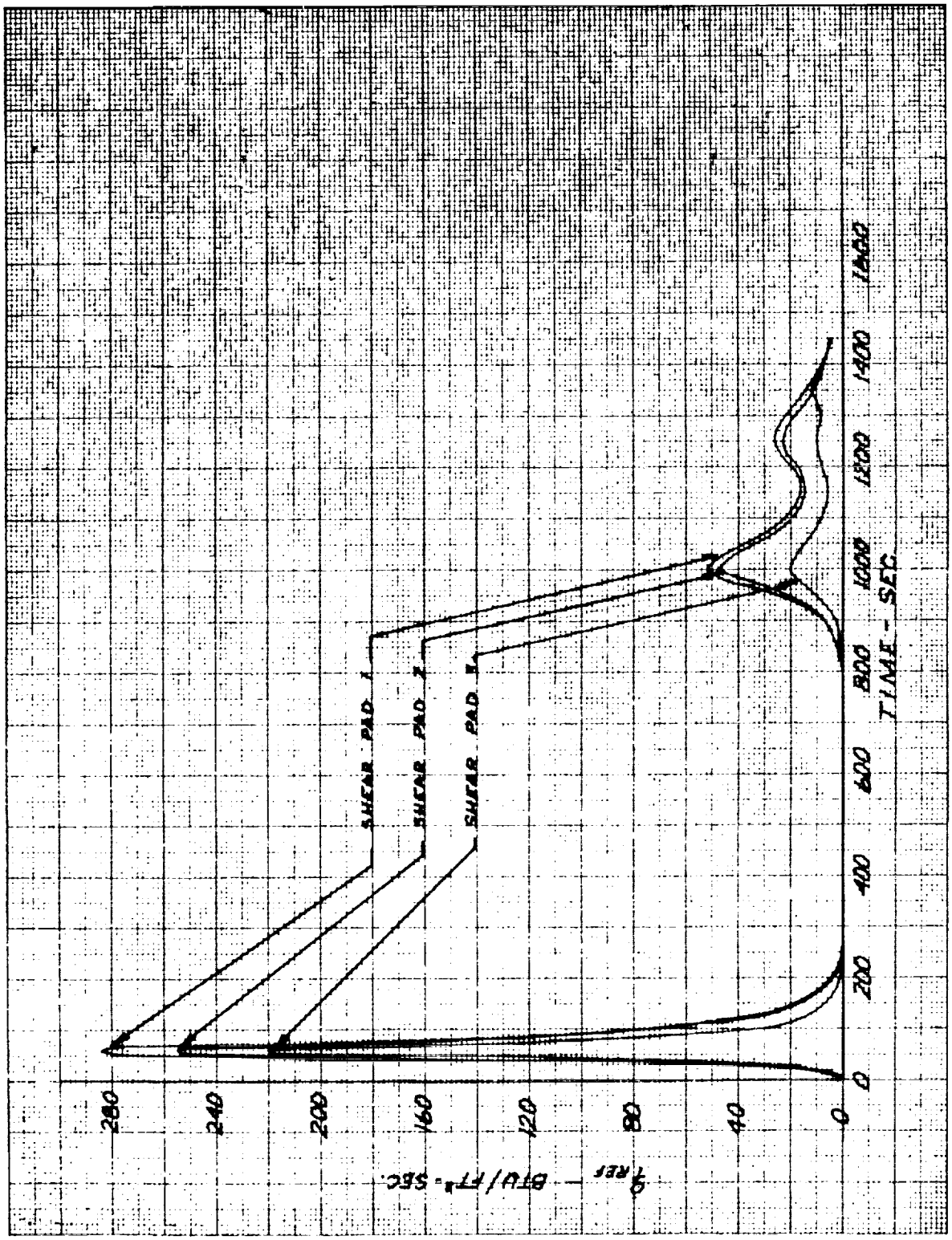

Figure 87. $\dot{q}_o$ Heating Rate Based on Trajectory HSE-4A

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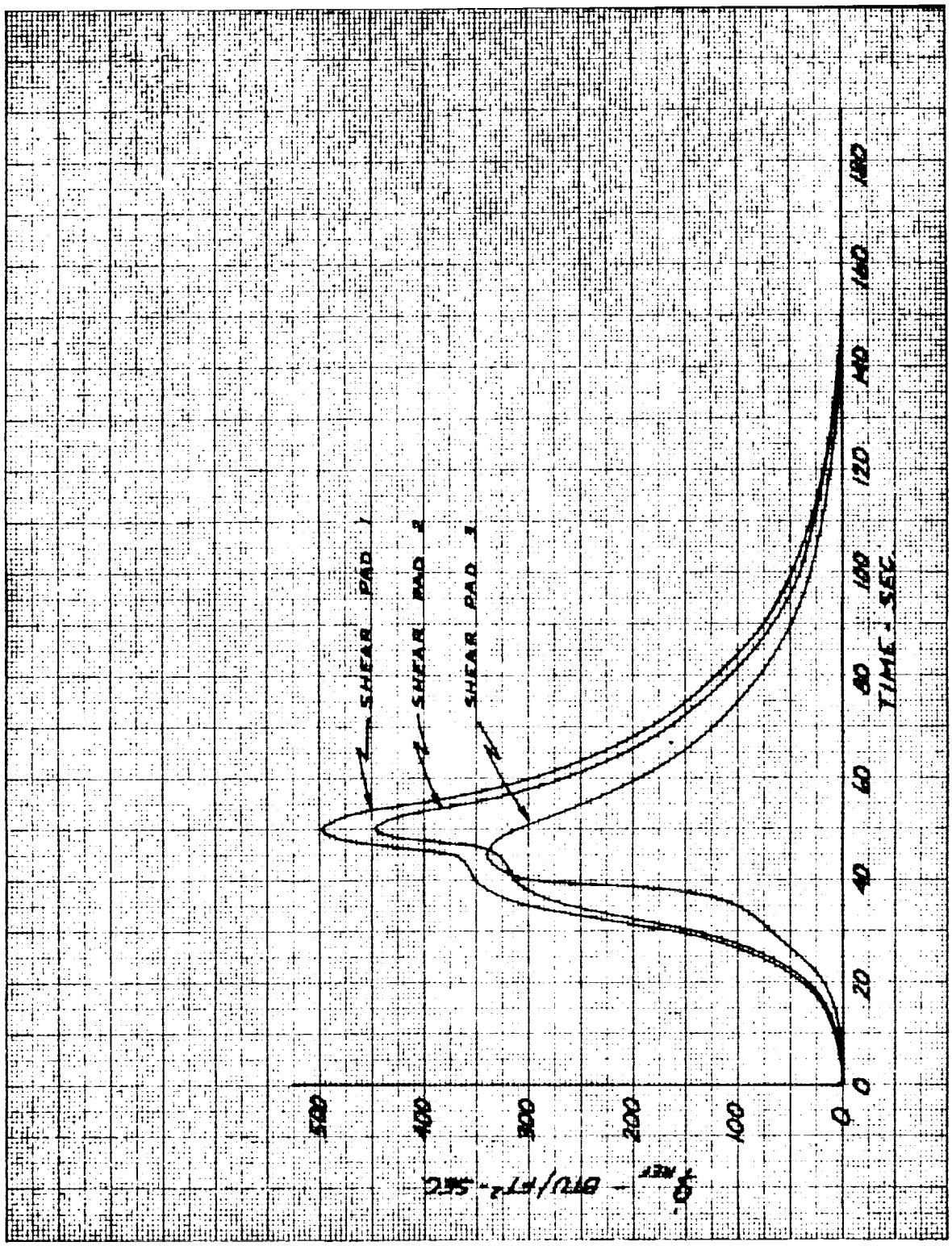

Figure 88. $\dot{q}_o$ Heating Rate Based on Trajectory HSE-6

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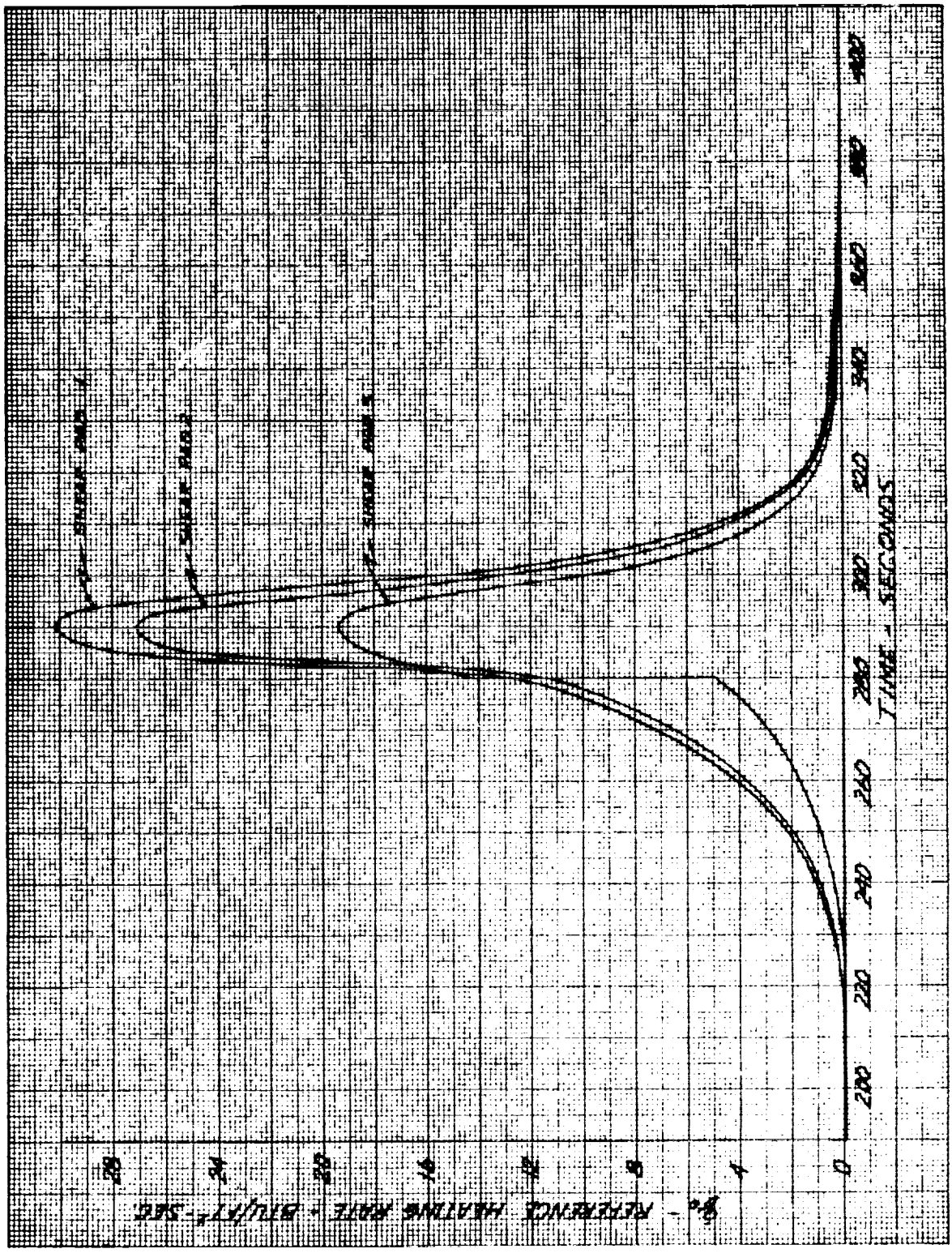

Figure 89. $\dot{q}_o$ Heating Rate Based on Trajectory HSA-3

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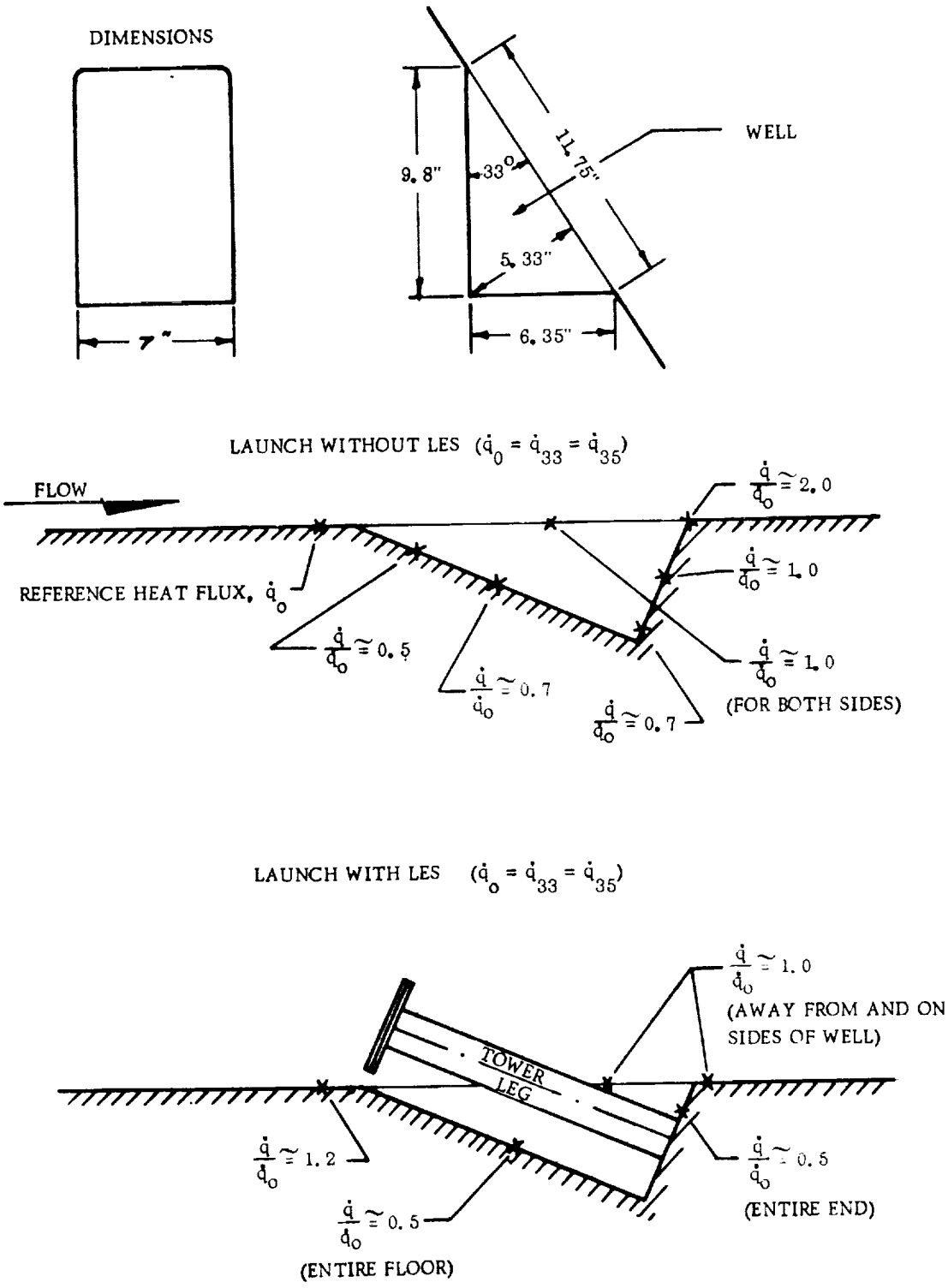

Figure 90. Heat Flux Ratios in Escape Tower Wells of Command Module

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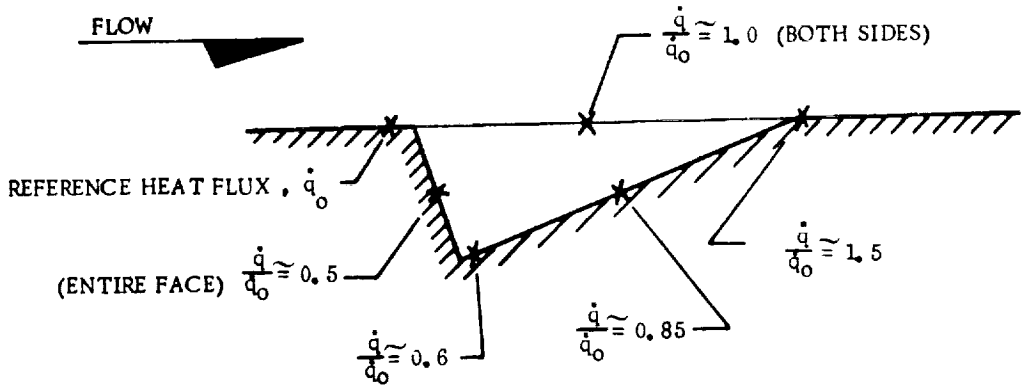

Figure 91. Heat Flux Ratios in Escape Tower Wells of Command Module

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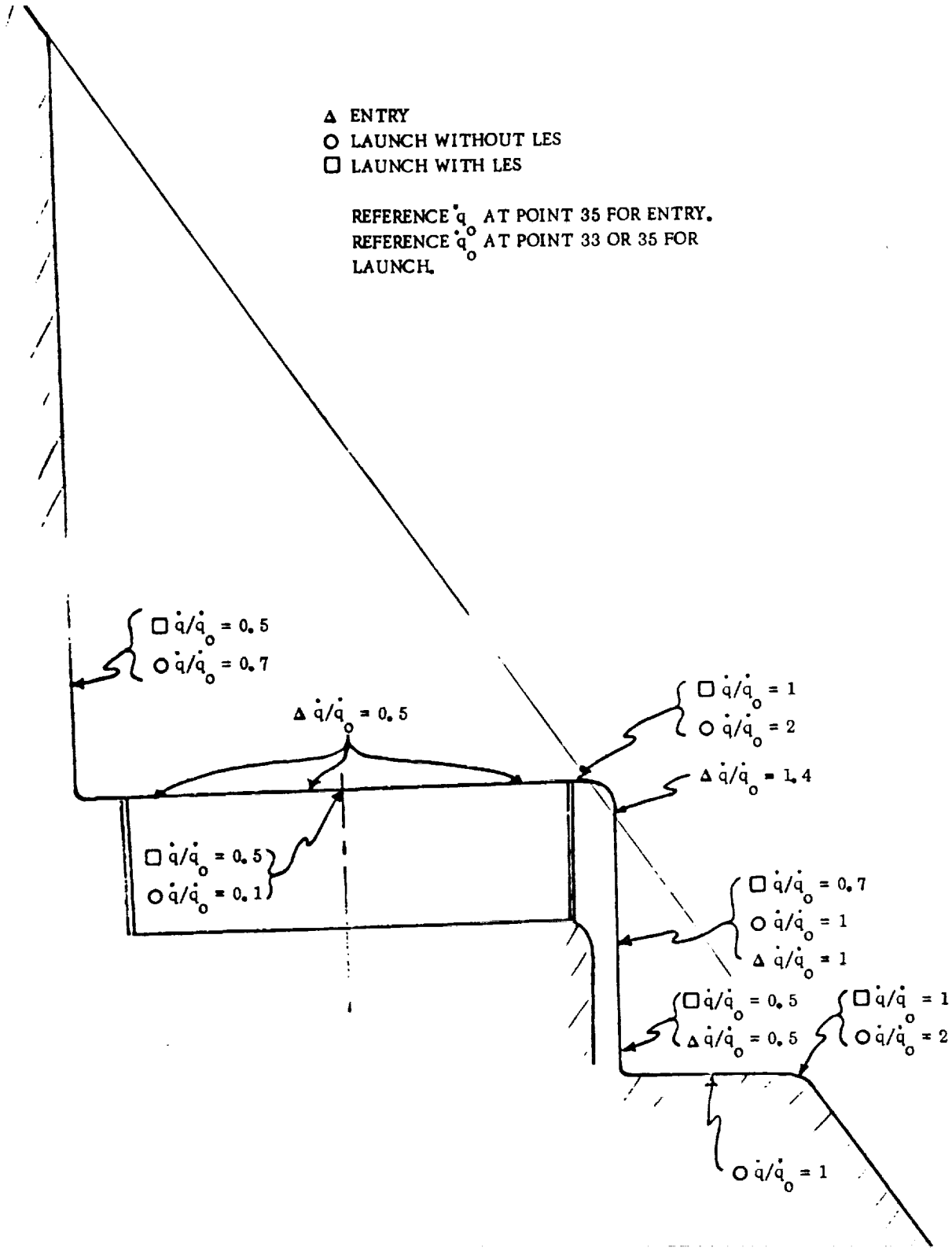

Figure 92. Heat Flux Ratios in Tower Well With Electrical Umbilical

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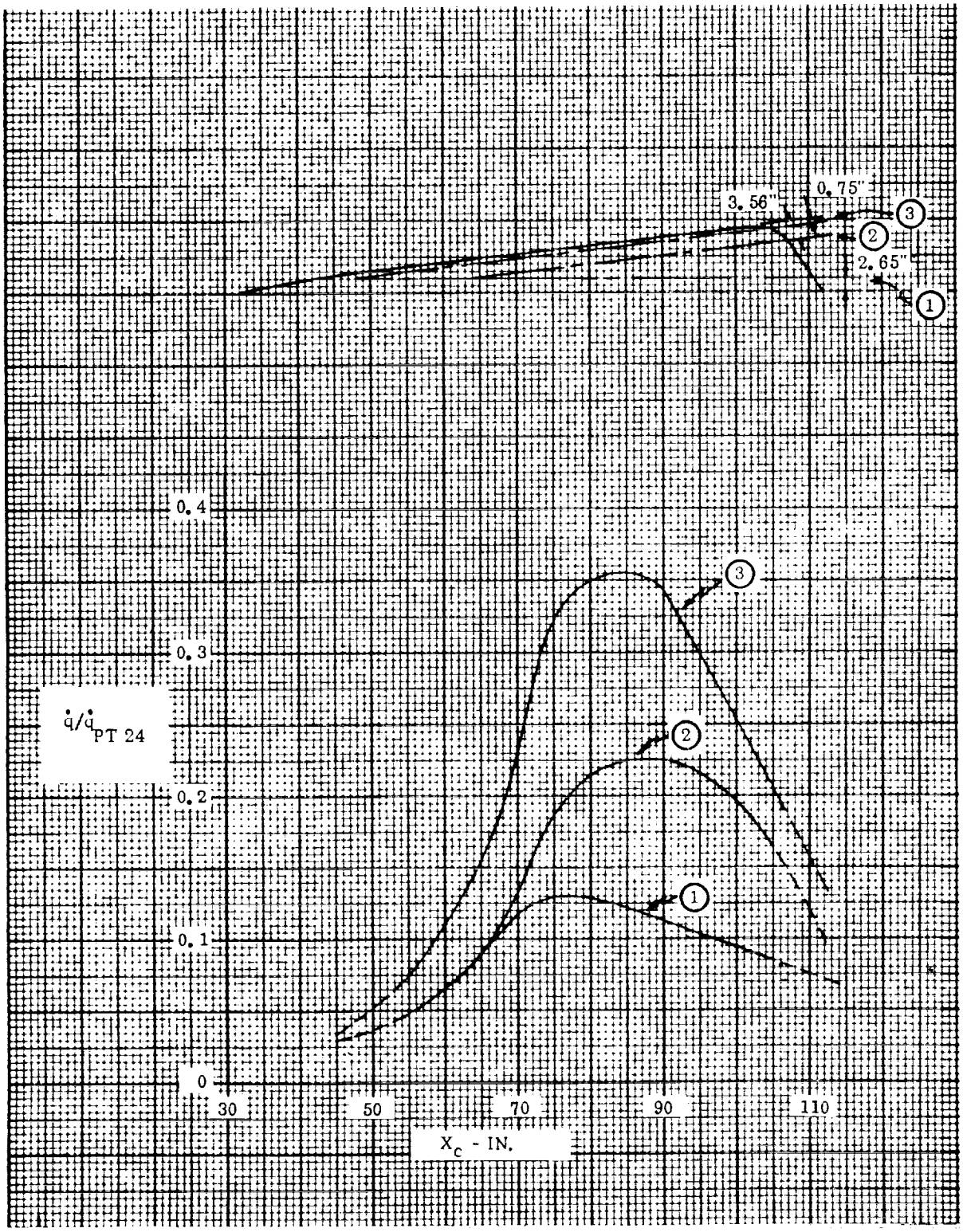

Figure 93. Heating Rate Distribution on Aerodynamic Strake During Entry

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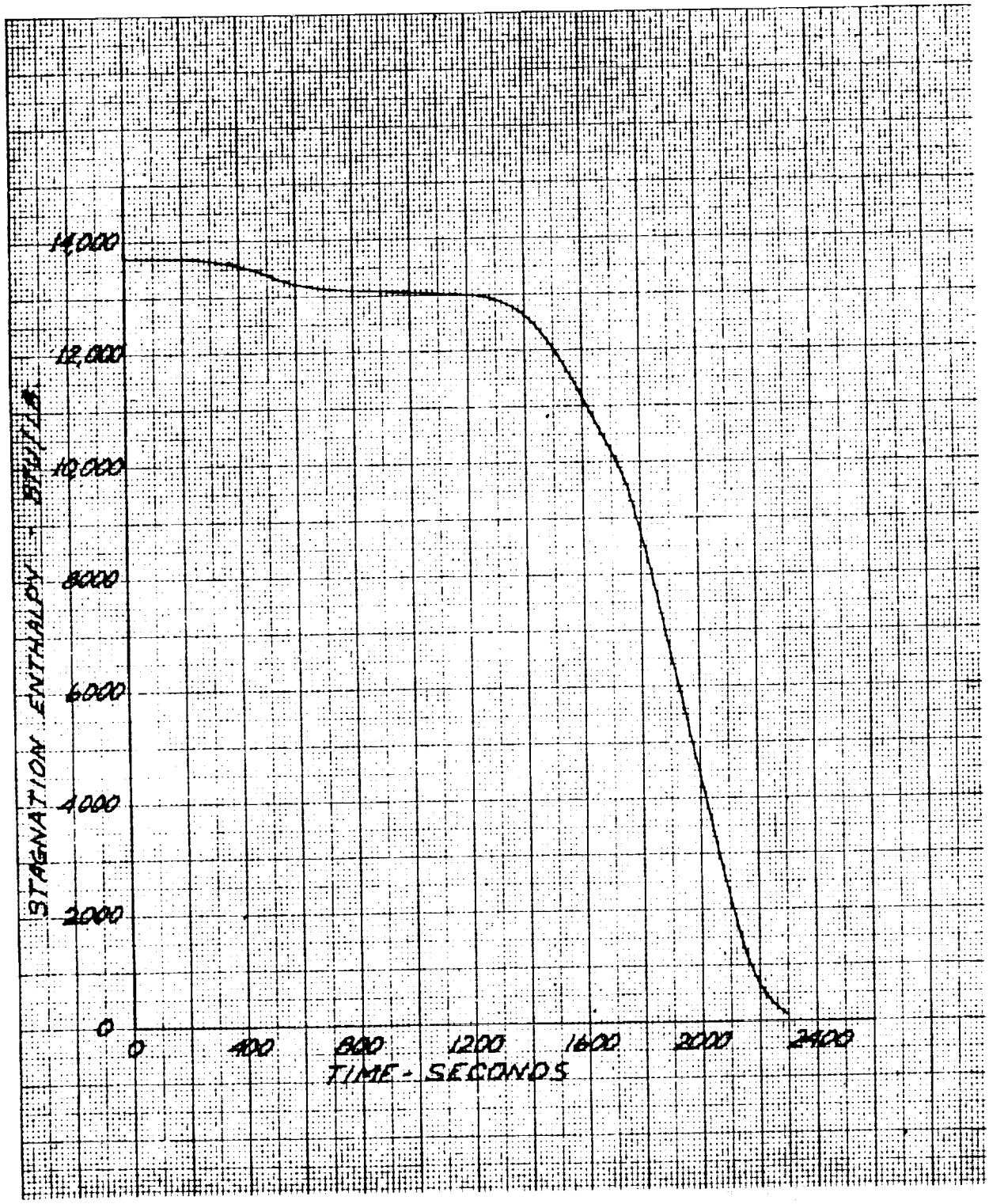

Figure 94. Stagnation Enthalpy Time History During Trajectory HSE-1

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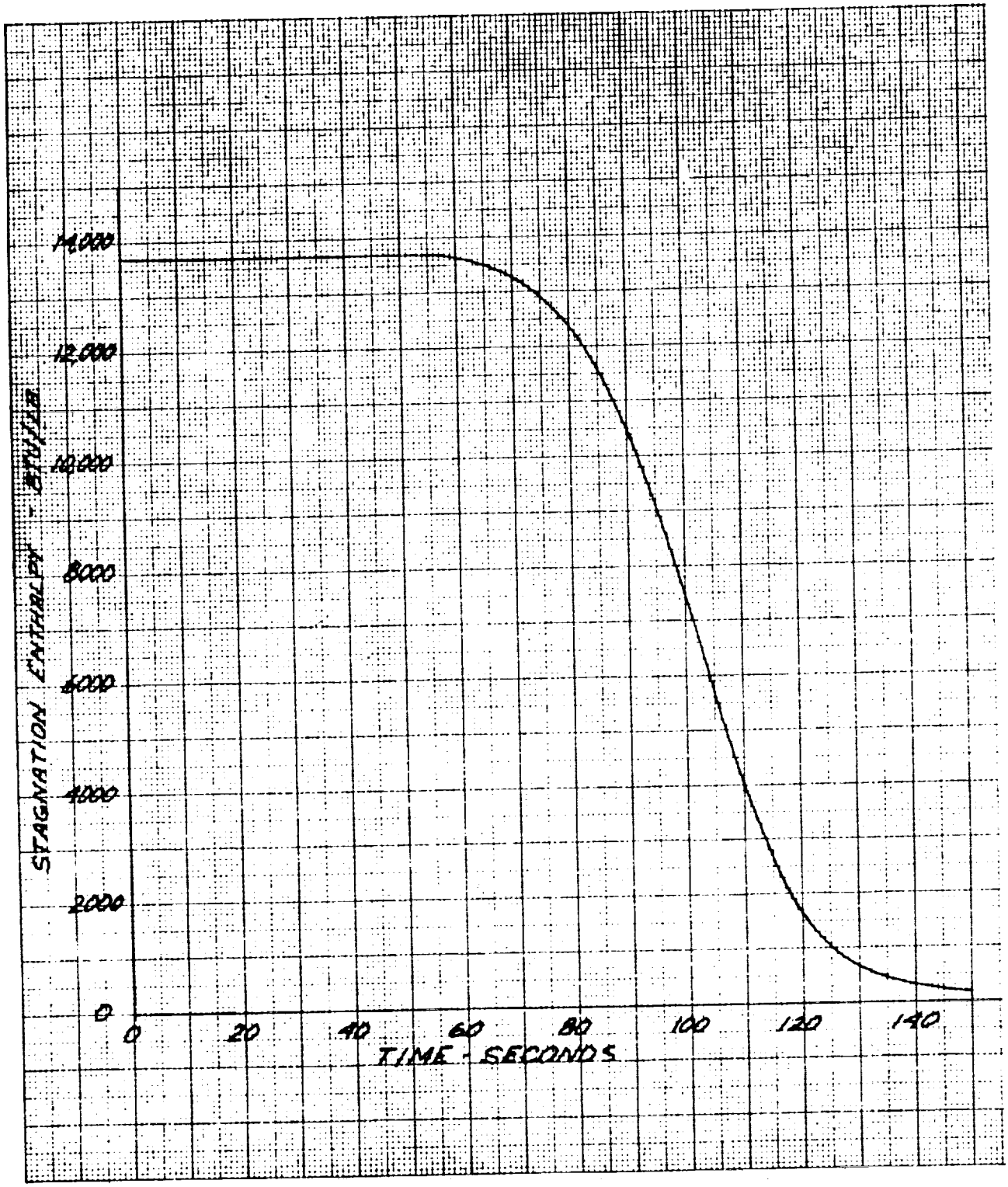

Figure 95. Stagnation Enthalpy Time History During Trajectory HSE-2

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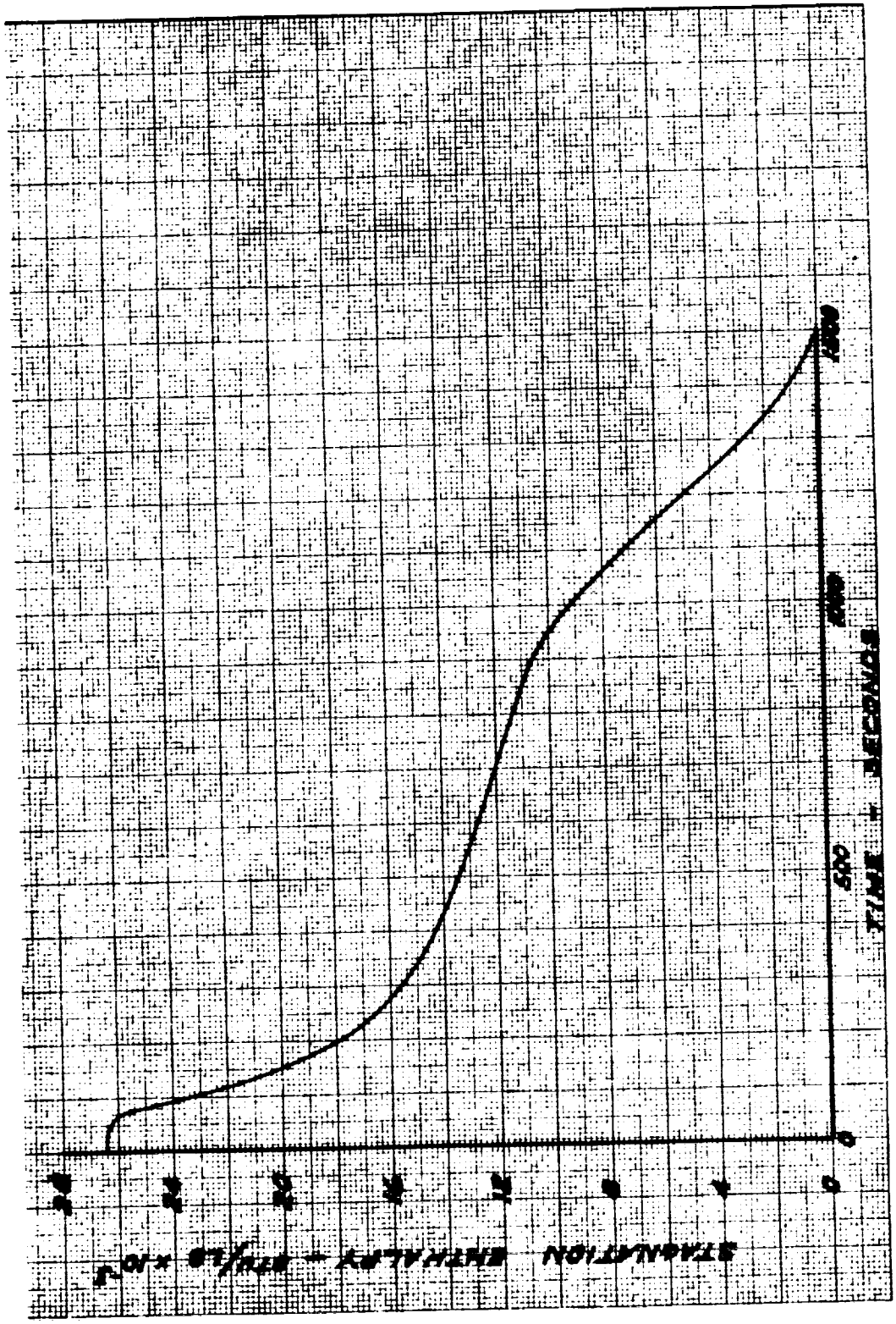

Figure 96. Stagnation Enthalpy Time History During Trajectory HSE-3A

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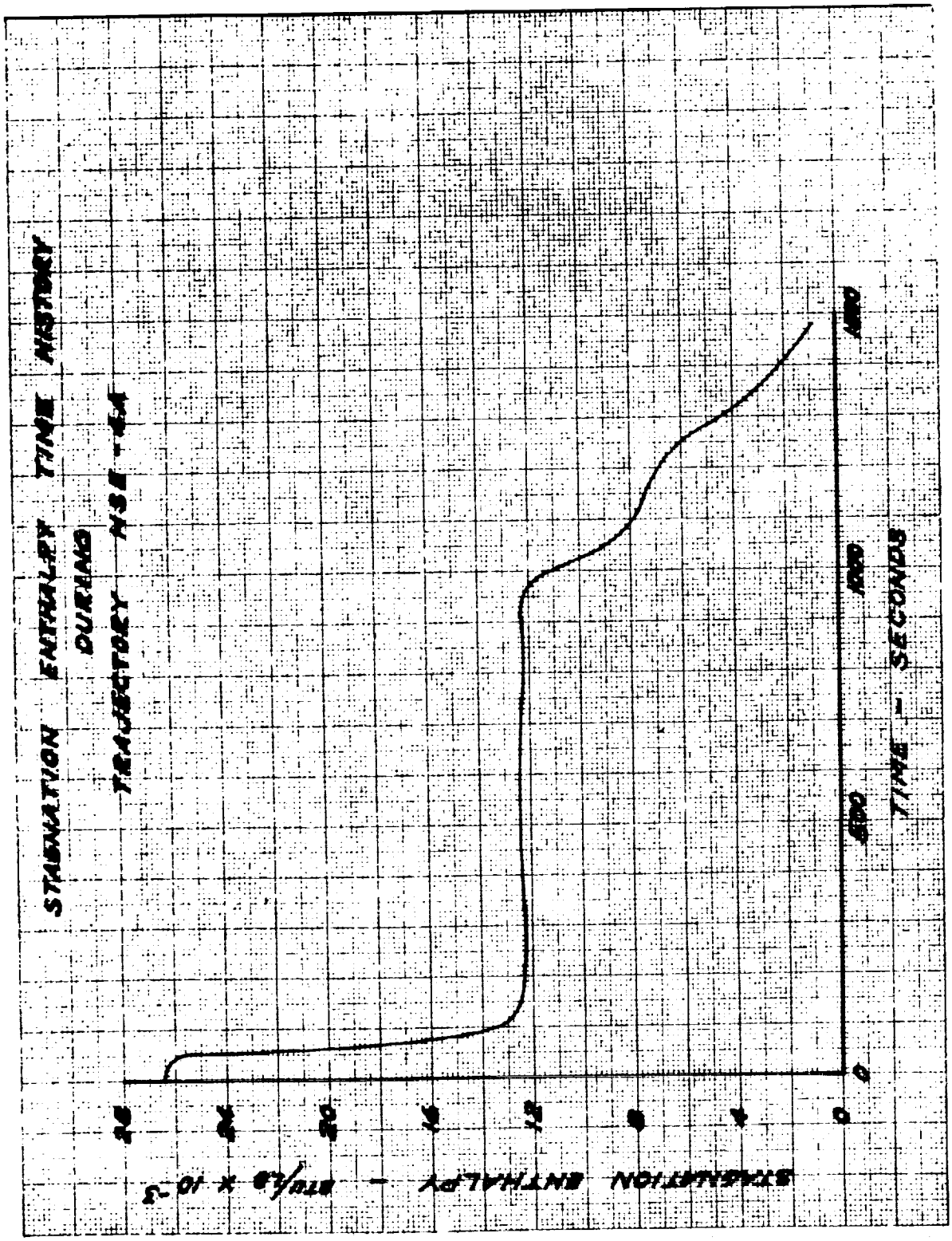

Figure 97. Stagnation Enthalpy Time History During Trajectory HSE-4A

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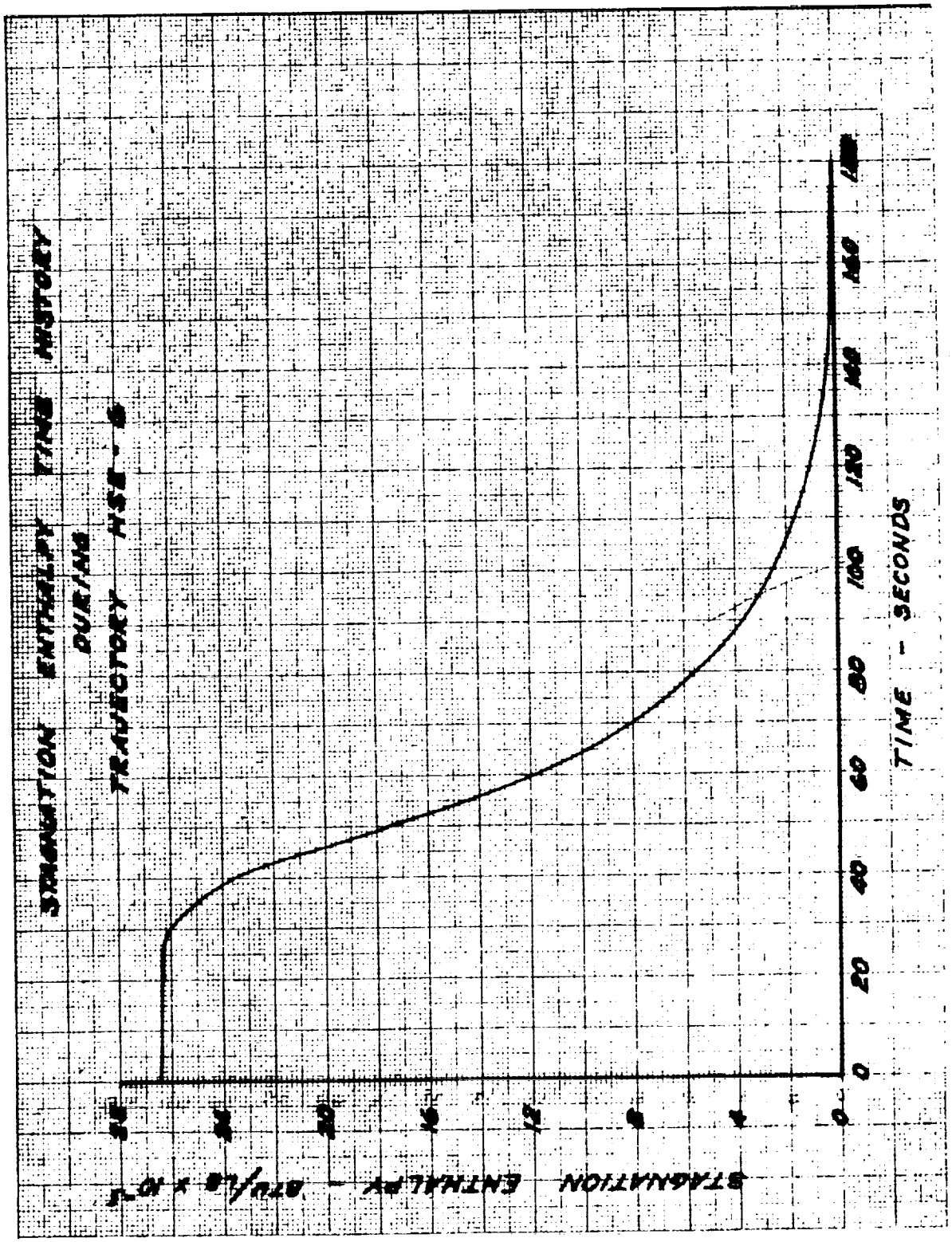

Figure 98. Stagnation Enthalpy Time History During Trajectory HSE-6

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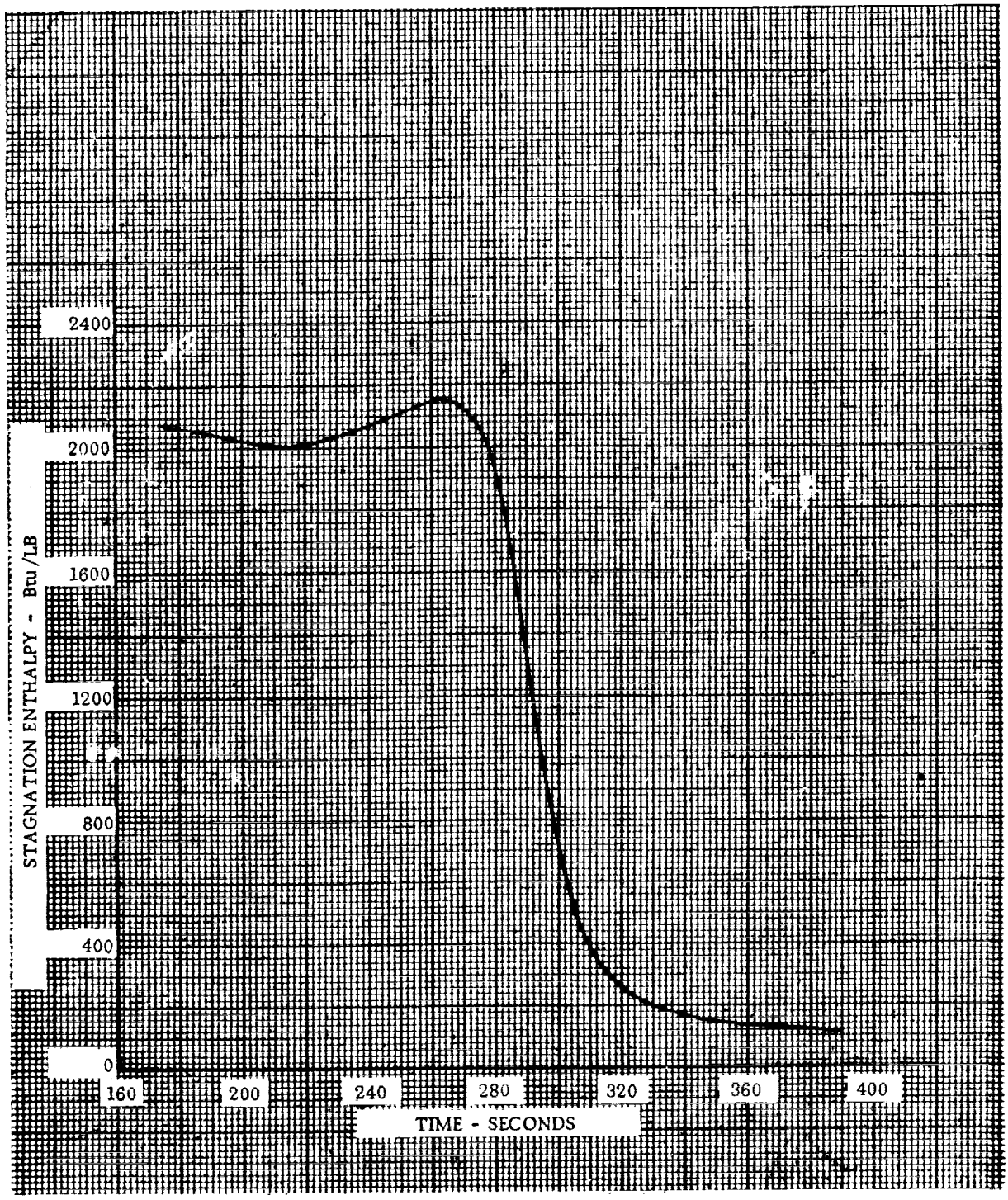

Figure 99. Stagnation Enthalpy Time History During Trajectory HSA-3

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