NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-712

Nozzle Exit Exhaust Products From Space Shuttle Boost Vehicle (November 1973 Design)

Solid Propellant Engineering Staff

(NASA-CR-136747) NOZZLE EXIT EXHAUST PRODUCTS FROM SPACE SHUTTLE BOOST VEHICLE (NOVEMBER 1973 DESIGN) (Jet Propulsion Lab.) 50 p HC $3.75 CSCL 21H

N75-19344

Unclas

G3/20 11722

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Prepared Under Contract No. NAS 7-100
National Aeronautics and Space Administration

PREFACE

The work described in this report was performed by the Propulsion Division of the Jet Propulsion Laboratory.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the information kindly supplied by Mr. W.L. Norton of the Downey Space Division of North American Rockwell, Mr. Klaus Gross of the Marshall Space Flight Center, and the helpful cooperation received from Mr. John Thirkill and Mr. Robert Lund of the Thiokol-Wasatch Division.

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ABSTRACT

Principal exhaust species emitted at various altitudes for two trajectories of the Space Shuttle Vehicle are presented. The exhaust composition is given for the nozzle exit plane on the basis of equilibrium chemistry. However, afterburning of excess H, H_2, and CO in the plume is accounted for. Species considered include HCl and Al_2O_3, which have been recognized as environmentally significant, as well as others such as H_2O (produced by both the Solid Rocket Motor and the Orbiter Main Engine) which, although innocuous, may participate in subsequent chemical reactions in the atmosphere.

I. INTRODUCTION

A number of changes have been introduced in the Space Shuttle Vehicle since the National Aeronautics and Space Administration (NASA) published its Environmental Statement in 1972 (Ref. 1). These changes affect the Solid Rocket Motor Boosters (SRM) and the mission profiles.

In this report, updated calculations of the principal exhaust species, using recent data on the SRMs and the mission profiles, are presented.

II. TRAJECTORY DATA AND BASIC MOTOR DATA

Trajectory data and solid rocket motor propellant mass flow data as functions of time for four missions were obtained from reports provided by North American Rockwell (Ref. 2). The reports were acquired in March 1974 and dated November 1973. The data are part of a package of flight dynamic data prepared for each major design change for each of the four missions.

Data on propellant mass flow rates and trajectories used in this report are given in Tables 1 and 2 and plotted in Fig. 1. Significantly, these data belong to the NASA standard SRM and not to the specific motor proposed by Thiokol. The final flight motor, however, may be different from both.

Two trajectories were chosen for the calculations: Mission 3B, which has the highest burnout altitude, 44.860 km, of the solid rocket motors, and Mission 2, which has the lowest burnout altitude, 41.647 km, of the solid rocket motors. The differences are small except near burnout, where the propellant mass flow of the solid rocket motor is also small.

The SRM propellant mass flows and the SRM time integrated propellant mass flows, as functions of altitude, are given in Fig. 2 and in Fig. 3, respectively.

III. SRM EMISSIONS

Equilibrium exit plane calculations for the Thiokol proposed SRM propellant were supplied by Thiokol (Ref. 3). The propellant is TPH-1123, and only small deviations from this propellant are to be expected. The calculations are based on a chamber pressure of 3.92×10^6 N/m^2 and on an exit pressure of 1.01×10^5 N/m^2. Chamber pressure of the SRM varies with time; the initial value is about 5.10×10^6 N/m^2. The design pressure history is proportional to the flow rate as shown in Fig. 1. The species considered in the Thiokol equilibrium calculations are shown in Table 3. The main components of the SRM exhaust, and their weight fractions, are shown in Table 4. The table shows the nine most abundant species which account for 99.87% of the total mass. The next most abundant quantity is hydrogen (H) at 0.000205.

SRM emissions of the major species into the atmosphere are shown in Tables 5a through 5d and plotted in Figs. 4a and 4b. Exit plane values are given for CO and H_2. In addition, complete conversion (by afterburning) to CO_2 and H_2O was calculated for CO and H_2, respectively. These quantities were added to the exit CO_2 and exit H_2O to obtain the burned CO_2 and burned H_2O. No attempt was made to predict the presence of species such as NO resulting from chemical kinetic processes occurring in the nozzle and in the plume since predictions of this nature exceed the scope of this study.

The production rates of the major species, to a given altitude, are given in Figs. 5a and 5b.

The data are presented in metric tons and in pounds for each specie released into the atmosphere in a given altitude band. At the lower altitudes, 2-second increments were used, increasing at moderate altitudes to 4-second increments. A small time increment was used because of the interest in the details of the ground cloud. At higher altitudes, the spacing shifts to 3-km bands. Errors due to changing flow rates were minimized either by taking smaller time increments when the slope of the mass flow curve changed, or by integrating each segment of the mass flow curve separately when a slope change occurred in the time interval, or both.

A comparison of the current calculations for the injectants emitted into the atmosphere with calculations published by the Institute of Defense Analysis (IDA) (Ref. 4) is shown in Fig. 6. Hydrochloric acid (HCl) was arbitrarily chosen for the comparison; however, any specie would perform equally well. The comparison shows that, for the present calculations, the results are higher and the profile somewhat different than the results and the profile for the IDA calculations. These discrepancies are due to both the mission profile and the specifications on the SRM changing frequently during the 1972 - 1973 time period after the generation of the data on which IDA calculations were based. There is still some doubt, however, that the current data are final.

IV. EMISSIONS FROM THE ORBITER MAIN ENGINE

The liquid propellant engine of the orbiter burns liquid hydrogen and liquid oxygen. Thus the primary exhaust product is water, with some hydrogen that will not afterburn at higher altitudes. In itself, the water has negligible environmental impact but it may interact with the exhaust from the SRM.

The following data were obtained from Mr. Klaus Gross of NASA Marshall Space Flight Center: chamber pressure = 2.048×10^7 N/m^2; mixture ratio = 6.0; exit area ratio = 77.5; flow rate = 465.75 kg/s. These are constant during the boost phase, except at tail-off. The mass fractions at the exit, obtained by a one-dimensional kinetic calculation, are shown in Table 6 in their order of importance.

The H_2O and H_2 emissions in each altitude band are shown in Tables 7a through 7d. Both burned and unburned options are shown between 45 and 60 km since the altitude at which afterburning ceases is not accurately known. The orbiter engine produces mostly H_2O; this is an appreciable contribution to the total H_2O produced by the shuttle vehicle. Total H_2O production up to SRM burnout altitude is also shown in Tables 7a through 7d. Total H_2O production rate as a function of altitude is given in Fig. 7.

V. CONCLUSIONS

Up to the altitude of SRM burnout, the emissions are only a weak function of mission; above this altitude, the orbiter main engine produces mostly water. The calculations presented here should be representative of almost any mission profile. Further updates in these calculations may be required for significant changes in the SRM, due to either design changes or to differences between actual performance and design.

The calculations presented here are only for the principal species in chemical equilibrium, including afterburning in the plume. Mechanisms currently being proposed as possible sources of stratospheric pollution involve chemical kinetics. Predictions of these effects would require chemical kinetic calculations in the nozzle and in the plume, as well as chemical kinetic calculations in the atmosphere after the vehicle has passed. Studies of chemical kinetics for this application are under way at various NASA centers and other institutions.

Knowledge of the mass rate of deposit of HCl and Al_2O_3 in the atmosphere is of little use without knowledge of particle size distributions for the Al_2O_3 and mechanisms of dispersion in the atmosphere for the particles and for the HCl. Studies of these factors are also in progress.

The principal contribution of this study is the results presented in the tables and figures of this report.

REFERENCES

1. "Environmental Statement for the Space Shuttle Program, Final Statement," NASA, July, 1972.
2. Norton, W. L., "Mission 3B Ascent Trajectories (MCR 0200 R-4 Configuration 4)," North American Rockwell Internal Document 393-140-73-057, Nov. 29, 1973, and "Mission 2 Ascent Trajectories (MCR 0200 R-4 Configuration 4)," North American Rockwell Internal Document 393-140-73-055, Nov. 29, 1973.
3. Thirkill, John, Thiokol, Personal Communication to Winston Gin, JPL, Feb. 1, 1974.
4. Oliver, R.C., "Space Shuttle and Stratospheric Pollution," Institute of Defense Analysis Interoffice Memorandum dated June 4, 1973.

Table 1. Performance profile of the SRMs

Time, s	Vacuum thrust, lb	Vacuum I_{sp}, s	Flow rate, lb/s	Propellant, lb
		Mission 3B		
0.0	5477491	266.72	20536.41	0.0
28.0000	5477491	266.30	20569.13	575478
48.6092	3784185	265.02	14278.77	934571
54.6092	3674535	264.86	13074.11	1019030
61.2719	3811684	264.85	14391.82	1113192
67.9345	3940892	264.84	14880.41	1210707
74.5971	4054419	264.81	15310.60	1311282
81.2598	4144424	264.77	15652.98	1414431
87.9224	4203067	264.71	15878.25	1519471
94.5851	4222508	264.62	15957.01	1625524
101.2477	4194905	264.50	15859.85	1731515
107.9104	4112417	264.35	15556.68	1835172
114.5730	3967205	264.16	15018.30	1939027
124.5730	200000	256.38	780.10	2017018
126.5730	200000	256.35	780.19	2018578
		Mission 2		
0.0	5553946	266.76	20819.57	0.0
27.6192	5553846	266.34	20852.73	575477
47.9481	3836935	265.07	14475.11	934566
53.6655	3725852	264.90	14064.89	1019021
60.4385	3854818	264.90	14589.69	1113180

Table 1 (continued)

Time, s	Vacuum thrust, lb	Vacuum I_{sp}, s	Flow rate, lb/s	Propellant, lb
Mission 2 (continued)				
67.0106	3995927	264.89	16085.00	1210691
73.5826	4110937	264.86	15521.11	1311263
80.1546	4202196	264.82	15860.19	1414408
86.7267	4261657	264.76	16096.59	1519444
93.2967	4281369	264.67	16176.41	1625493
99.8707	4253381	284.55	16077.78	1731480
106.4428	4189743	264.40	15770.69	1935175
113.0149	4022507	264.21	15224.94	1937986
122.8788	202788	255.42	790.84	2016975
124.8516	202788	256.39	790.93	2018535

Table 2. Main engine performance profile

Time, s	Weight, lb	Altitude, ft	Thrust, lb
Mission 3B			
0.0	4140866	0.0	1123385
2.0	4093595	31.2	1123707
4.0	4046321	126.1	1124687
6.0	3999041	287.1	1126341
8.0	3951757	516.4	1128682
10.0	3904468	816.4	1131716
12.0	3857175	1189.5	1135447
14.0	3809877	1639.1	1139871
16.0	3762574	2164.5	1144976
18.0	3715267	2771.0	1150748
20.0	3667955	3460.1	1157165
22.0	3620638	4234.1	1164198
24.0	3573316	5095.3	1171814
26.0	3525990	6045.8	1179973
28.0	3478659	7087.8	1188631
30.0	3431884	8222.8	1197735
32.0	3386383	9447.7	1207194
34.0	3342103	10758.8	1216917
36.0	3299043	12152.1	1226818
38.0	3257204	13623.4	1236813
40.0	3216585	15168.7	1246826

Table 2 (continued)

Time, s	Weight, lb	Altitude, ft	Thrust, lb
Mission 3B (continued)			
42.0	3177188	16783.2	1256786
44.0	3139011	18462.4	1266626
46.0	3102056	20201.2	1276285
48.0	3066322	21994.5	1285707
50.0	3031576	23836.9	1294841
52.0	2997142	25725.6	1303654
54.0	2962979	27659.8	1312124
56.0	2928947	29638.2	1320228
58.0	2894632	31662.3	1327956
60.0	2850005	33735.0	1335321
62.0	2825071	35858.6	1342339
64.0	2789841	38035.9	1348929
66.0	2754317	40270.1	1355092
68.0	2718499	42564.3	1360931
70.0	2692406	44921.2	1365149
72.0	2646055	47344.0	1371052
74.0	2609446	49835.6	1375548
76.0	2572592	52398.9	1379648
78.0	2535530	55036.9	1383366
80.0	2498264	57752.3	1386718
82.0	2460795	60548.2	1389709

Table 2 (continued)

Time, s	Weight, lb	Altitude, ft	Thrust, lb
Mission 3B (continued)			
84.0	2423178	63427.4	1392353
86.0	2385425	66392.4	1394724
88.0	2347537	69446.1	1398829
90.0	2309561	72590.9	1398680
92.0	2271536	75829.2	1400298
94.0	2233465	79163.2	1401705
96.0	2195375	82595.1	1402926
98.0	2157338	86126.9	1403985
100.0	2119359	89760.1	1404911
102.0	2081446	93496.8	1405715
104.0	2043694	97338.6	1406395
106.0	2006122	101286.7	1406977
108.0	1968733	105342.9	1407473
110.0	1931601	109508.4	1407894
112.0	1894792	113784.1	1408249
114.0	1858308	118171.2	1408547
116.0	1823584	122668.7	1408797
118.0	1794260	127258.4	1409005
120.0	1770637	131911.9	1409176
122.0	1752709	136599.4	1409317
124.0	1740477	141290.4	1409432
126.0	1732415	145956.0	1409526

Table 2 (continued)

Time, s	Weight, lb	Altitude, ft	Thrust, lb
Mission 3B (continued)			
126.5[a]	1730369	147185.3	1409548
126.5	1421868	147185.3	1409548
128.0	1417313	150585.1	1409603
144.0	1367753	186292.6	1409898
160.0	1318193	219759.3	1409974
176.0	1268633	251115.7	1409994
192.0	1219073	280470.4	1409998
208.0	1169513	307921.1	1409999
224.0	1119954	333560.2	1409999
240.0	1070394	357475.7	1410000
256.0	1020834	379751.6	
272.0	971274	400467.5	
288.0	921714	419698.2	
304.0	872154	437514.0	
320.0	822594	453979.6	
323.8	810804	457704.7	
336.0	773034	469153.6	
352.0	723474	483087.8	
368.0	673914	495829.2	
384.0	624354	507419.4	1410000

[a]End of Stage 1.

Table 2 (continued)

Time, s	Weight, lb	Altitude, ft	Thrust, lb
Mission 3B (continued)			
400.0	574794	517894.3	1410000
416.0	525235	527286.7	1410000
432.0	475675	535626.9	1410000
433.8	470166	536490.3	1410000
448.0	428118	542909.7	1283681
464.0	385299	548948.9	1155046
480.0	346770	553552.4	1039303
496.0	312103	556605.4	935158
511.9[b]	281171	558070.0	842235
Mission 2			
0.0	4187153	0.0	1123941
2.0	4139316	31.3	1124253
4.0	4091475	126.8	1125202
6.0	4043629	288.7	1126805
8.0	3995778	519.3	1129077
10.0	3947922	820.9	1132027
12.0	3900052	1196.0	1135659
14.0	3852196	1646.9	1139975
16.0	3804326	2175.8	1144988
18.0	3756451	2785.2	1150628

[b]Begin coast.

Table 2 (continued)

Time, s	Weight, lb	Altitude, ft	Thrust, lb
Mission 2 (continued)			
20.0	3708572	3477.4	1156935
22.0	3660687	4254.6	1163865
24.0	3612798	5119.0	1171388
26.0	3564904	6072.7	1179464
28.0	3517044	7117.9	1188051
30.0	3470011	8254.7	1197085
32.0	3424218	9479.9	1206474
34.0	3379689	10789.5	1216122
36.0	3336417	12179.1	1225939
38.0	3294398	13644.5	1235840
40.0	3253633	15181.2	1245744
42.0	3214123	16784.4	1255578
44.0	3175868	18449.1	1265275
46.0	3138868	20170.2	1274777
48.0	3103119	21942.2	1284031
50.0	3069154	23760.0	1292993
52.0	3033428	25621.9	1301645
54.0	2998979	27526.4	1309966
56.0	2964478	29472.6	1317946
58.0	2929655	31462.1	1325582
60.0	2894517	33497.0	1332872
62.0	2859062	35579.6	1339821

Table 2 (continued)

Time, s	Weight, lb	Altitude, ft	Thrust, lb
Mission 2 (continued)			
64.0	2823304	37711.9	1346414
66.0	2787245	39896.5	1352640
68.0	2750898	42135.7	1358469
70.0	2714263	44431.8	1363955
72.0	2677372	46737.1	1369033
74.0	2640218	49204.2	1373720
76.0	2602854	51685.5	1378015
78.0	2565306	54233.2	1361921
80.0	2527575	56849.6	1385440
82.0	2489662	59537.2	1388559
84.0	2451562	62298.3	1391327
86.0	2413338	65135.2	1393779
88.0	2374951	68050.1	1395943
90.0	2336510	71045.1	1397848
92.0	2298021	74121.8	1399321
94.0	2259488	77282.1	1400984
96.0	2220993	80527.5	1402262
98.0	2182557	83859.2	1403373
100.0	2144182	87278.6	1404339
102.0	2105936	90786.8	1405177
104.0	2067875	94384.8	1405904
106.0	2030003	98073.5	1406529

Table 2 (continued)

Time, s	Weight, lb	Altitude, ft	Thrust, lb
Mission 2 (continued)			
108.0	1992363	101853.7	1407065
110.0	1955049	105726.2	1407524
112.0	1918067	109691.4	1407915
114.0	1882015	113749.3	1408247
116.0	1851120	117887.4	1408529
118.0	1826074	122080.2	1408765
120.0	1806879	126300.1	1408962
122.0	1793535	130519.4	1409125
124.0	1785326	134710.4	1409260
124.9[a]	1781670	136635.6	1409315
124.9	1473169	136635.6	1409315
128.0	1463645	142963.2	1409465
144.0	1414085	174205.4	1409937
160.0	1364525	202763.9	1409949
176.0	1314965	228811.7	1409983
192.0	1265405	252507.8	1409994
208.0	1215846	274010.8	1409998
224.0	1166286	293481.8	1409999
240.0	1116726	311097.4	1409999
256.0	1067166	327044.2	1409999

[a]End of Stage 1.

Table 2 (continued)

Time, s	Weight, lb	Altitude, ft	Thrust, lb
Mission 2 (continued)			
272.0	1017607	341526.9	1410000
274.3[c]	1010388	343527.2	
288.0	968046	354322.2	
304.0	918486	364841.2	
320.0	868925	373210.5	
336.0	819365	379585.1	
352.0	769805	384139.8	
368.0	720244	387073.4	
384.0	670684	388614.4	
400.0	621123	389028.1	
416.0	571563	386625.7	
432.0	522002	387776.4	
448.0	472442	388923.2	
448.7	470216	386892.9	1410000
464.0	425189	326545.4	1274769
480.0	382666	366953.4	1147061
496.0	344403	388462.4	1032148
509.3	315554	390833.6	945533
509.3	315564	390833.6	0.0

[c]Begin Nominal Ascent.

Table 3. Chemical species considered in Thiokol equilibrium calculations[a,b]

Al	Al_2O_3(l)	CH_2Cl_2	C_2H_4O	Cl_3Fe	H_3N
AlCl	Al_2O_3(s)	CH_2O	C_2N	Cl_4Fe_2	H_3O^+
$AlCl^+$	C	CH_3	C_2O	Cl_6Fe_2	H_4N_2
AlClO	CAl	CN	C_3	e^- (free electron)	N
$AlCl_2$	CCl	CN^+	C_3O_2	Fe	NHO_2
$AlCl_2^-$	CClN	CN^-	C_4	FeH_2O_2	NO
$AlCl_2^+$	CClO	CNO	C_4N_2	FeO	NO^+
$AlCl_3$	CCl_2	CN_2	C_5	H	NO_2
Al^+	CCl_2O	CO	Cl	HAlO	NO_2^-
AlH	CCl_3	CO_2	Cl^-	H^-	NO_3
AlHO	CCl_4	CO_2^-	Cl^+	H^+	N_2
$AlHO^+$	C^-	C_2	ClFe	HN	N_2C
$AlHO^-$	CH	C_2Cl_2	ClH	HNO	N_2O
$AlHO_2$	CHCl	C_2Cl_4	ClHO	HNO_2	N_2O^+
AlN	$CHCl_3$	C_2Cl_6	ClNO	HNO_3	N_2O_3
AlO	CH^+	C_2^-	$ClNO_2$	HO^+	N_2O_4
AlO^+	CHN	C_2H	ClO	HO_2	N_2O_5
AlO_2	CHNO	C_2HCl	ClO_2	H_2	N_3
AlO_2^-	CHO	C_2H_2	Cl_2	H_2N	O
Al_2Cl_6	CHO^+	C_2H_4	Cl_2Fe	H_2N_2	O^-
Al_2O	CH_2		Cl_2O	H_2O	O_2
Al_2O^+				H_2O_2	O_2^-
Al_2O_2					O_3
$Al_2O_2^+$					

[a] All species are in the gaseous phase except as noted.

[b] The notation used is that adopted by the Joint Army-Navy-NASA Air Force (JANNAF) where AlHO denotes aluminum monoxyhydride, HAlO denotes aluminum monohydroxide, HNO_2 denotes nitrous acid cis- and NHO_2 denotes nitrous acid trans-.

Table 4. Weight fractions of SRM exhaust components[a,b,c]

Exhaust components	Weight, %
$Al_2O_3(s)$	0.3020
CO	0.2417
HCl	0.2093
H_2O	0.0943
N_2	0.0874
CO_2	0.0344
H_2	0.0208
Cl	0.00287
$FeCl_2$	0.00594

[a]All components are in the gaseous phase unless otherwise indicated.

[b]Chlorine also appears as Cl_2 and in other forms in smaller quantities.

[c]$FeCl_2$ and Cl are included to provide an estimate of the amount of chlorine available in the exhaust for further reactions.

Altitude band, km	Δaltitude, km	Time, s	Δtime, s	Average mass flow, 10^3 kg/s	Mass, 10^3 kg	Exhaust products[a] Al_2O_3	HCl	CO	CO_2
						0.302028	0.209315	0.241719	0.0343946
								Exit	Exit
0-0.0095	0.0095	0-2	2	9.316	18.64	5.629	3.901	4.505	0.6411
0.0095-0.038	0.0285	2-4		9.317		5.630	3.902	4.506	0.6411
0.038-0.088	0.050	4-6		9.318		5.630	3.902	4.506	0.6412
0.088-0.160	0.072	6-8		9.319	18.64	5.631	3.903	4.507	0.6413
0.16-0.25	0.090	8-10		9.320	18.65	5.632	3.903	4.507	0.6413
0.25-0.36	0.11	10-12		9.321		5.632	3.903	4.508	0.6414
0.36-0.50	0.14	12-14		9.322		5.633	3.904	4.508	0.6415
0.50-0.66	0.16	14-16		9.323		5.634	3.904	4.509	0.6416
0.66-0.84	0.18	16-18		9.324	18.65	5.634	3.905	4.509	0.6416
0.84-1.06	0.22	18-20	2	9.326	18.66	5.635	3.905	4.510	0.6417
1.06-1.55	0.49	20-24	4	9.327	37.3	11.27	7.812	9.021	1.284
1.55-2.16	0.61	24-28	4	9.329	37.33	11.27	7.814	9.023	1.284
2.16-2.51	0.35	28-30	2	9.189	18.39	5.553	3.848	4.444	0.6323
2.51-3.28	0.77	30-34	4	8.768	35.08	10.60	7.344	8.481	1.207
3.28-4.15	0.87	24-38		8.206	32.83	9.917	6.873	7.937	1.129
4.15-5.12	0.96	38-42	4	7.507	31.584	9.237	6.402	7.395	1.052
5.12-6.00	0.88	42-45.4	3.4	7.116	24.202	7.310	5.066	5.850	0.8324
6-9	3	45.4-55.8	10.4	6.473	67.34	20.34	14.10	16.28	2.316
9-12		55.8-65.19	9.39	6.493	60.99	18.42	12.77	14.74	2.098
12-15		65.19-73.50	8.31	6.780	56.36	17.02	11.80	13.62	1.939
15-18		73.50-80.90	7.40	7.001	52.49	15.85	10.99	12.69	1.805
18-21		80.90-87.63	6.73	7.144	48.09	14.53	10.07	11.62	1.654
21-24		87.63-93.75	6.12	7.215	44.17	13.34	9.245	10.68	1.519
24-27		93.75-99.40	5.65	7.221	40.81	12.33	8.543	9.865	1.404
27-30		99.40-104.6	5.20	7.179	37.34	11.28	7.816	9.026	1.284
30-33		104.6-109.4	4.80	7.075	33.97	10.26	7.111	8.212	1.168
33-36		109.4-113.9	4.50	6.894	31.03	9.373	6.496	7.502	1.067
36-39		113.9-118.3	4.40	5.582	24.57	7.420	5.142	5.938	0.8450
39-42	3	118.3-122.6	4.30	3.011	12.95	3.912	2.711	3.131	0.4455
42-44.9	2.9	122.6-126.57	3.97	0.8228	3.267	0.9868	0.6839	0.7898	0.1124
			TOTAL		915.6	276.5	191.7	221.3	31.49

[a]The mass is indicated below the symbol for each specie.

Table 5a. Exhaust products released into atmosphere by space shuttle SRMs: Mission 3B (metric tons per altitude band per flight)

Exhaust products[a]								
CO_2	H_2O		H_2	N_2	$FeCl_2$	Cl	Fe	H
0.4141894	0.0942778	0.2822035	0.0208249	0.0874651	0.00594356	0.0028753	0.000155655	0.000205127
Burned	Exit	Burned	Exit					
7.720	1.757	5.260	0.3881	1.630	0.1108	0.0536	2.901 E-3	3.823 E-3
7.720	1.757	5.260	0.3882	1.630			2.901	3.824
7.721	1.758	5.261	0.3882	1.631			2.902	3.824
7.722		5.262	0.3883				2.902	3.824
7.723		5.262	0.3883				2.902	3.825
7.724		5.263	0.3883		0.1108		2.903	3.825
7.725	1.758	5.263	0.3884		0.1109		2.903	3.826
7.726	1.759	5.264	0.3884	1.631			2.903	3.826
7.726	1.759	5.264	0.3885	1.632			2.904	3.827
7.728	1.759	5.265	0.3885	1.632	0.1109	0.0536	2.904	3.827
15.46	3.518	10.53	0.7772	3.264	0.2218	0.1073	5.809	7.655
15.46	3.519	10.53	0.7774	3.265	0.2219	0.1073	5.810	7.657
7.615	1.733	5.188	0.3829	1.608	0.1093	0.0529	2.862	3.771
14.53	3.308	9.901	0.7306	3.069	0.2085	0.1009	5.461	7.197
13.60	3.095	9.266	0.6838	2.872	0.1951	0.0944	5.111	6.735
12.67	2.883	8.631	0.6369	2.675	0.1818	0.0879	4.761	6.274
10.02	2.282	6.830	0.5040	2.117	0.1438	0.0696	3.767	4.965
27.89	6.349	19.00	1.402	5.890	0.4002	0.1936	10.482	13.813
25.26	5.750	17.21	1.270	5.335	0.3625	0.1754	9.494	12.511
23.34	5.313	15.91	1.174	4.930	0.3350	0.1621	8.773	11.561
21.74	4.949	14.81	1.093	4.591	0.3120	0.1509	8.171	10.767
19.92	4.534	13.57	1.002	4.206	0.2858	0.1383	7.486	9.865
18.29	4.164	12.46	0.9198	3.863	0.2625	0.1270	6.875	9.060
16.90	3.848	11.52	0.8499	3.570	0.2426	0.1174	6.353	8.372
15.47	3.520	10.54	0.7776	3.266	0.2219	0.1074	5.812	7.660
14.07	3.203	9.587	0.7075	2.971	0.2019	0.0977	5.288	6.969
12.85	2.926	8.755	0.6463	2.714	0.1845	0.0892	4.831	6.366
10.18	2.316	6.933	0.5116	2.149	0.1460	0.0706	3.824	5.039
5.364	1.221	3.655	0.2697	1.133	0.0770	0.0372	2.016 E-3	2.657 E-3
1.353	0.3080	0.9220	0.0680	0.2858	0.0194	9.394 E-3	5.086 E-4	6.702 E-4
379.2	86.32	258.4	19.07	80.08	5.442	2.633	0.1425	0.1878

Altitude band, km	Δaltitude, km	Time, s	Δtime, s	Average mass flow, 10^3 lb/s	Mass, 10^3 lb	Exhaust products[a]			
						Al_2O_3	HCl	CO	CO_2
						0.302028	0.209315	0.241719	0.0343946
								Exit	Exit
0-0.0095	0.0095	0-2	2	20538	41090	12410	8601	9932	1413
0.0095-0.038	0.0285	2-4		20540	41094	12412	8602	9933	1413
0.038-0.088	0.050	4-6		20542	41098	12413	8602	9934	1414
0.088-0.160	0.072	6-8		20545	41104	12415	8604	9936	
0.16-0.25	0.090	8-10		20547	41108	12416	8605	9937	
0.25-0.36	0.11	10-12		20549	41112	12417	8605	9938	
0.36-0.50	0.14	12-14		20552	41118	12419	8607	9939	
0.50-0.66	0.16	14-16		20554	41122	12420	8607	9940	1414
0.66-0.84	0.18	16-18		20556	41126	12421	8608	9941	1415
0.84-1.06	0.22	18-20	2	20559	41132	12423	8610	9942	1415
1.06-1.55	0.49	20-24	4	20562	82276	24850	17222	19888	2830
1.55-2.16	0.61	24-28	4	20567	82296	24856	17226	19894	2831
2.16-2.51	0.35	28-30	2	20259	40532	12242	8484	9797	1394
2.51-3.28	0.77	30-34	4	19330	77347	23361	16190	18697	2660
3.28-4.15	0.87	34-38		18090	72385	21863	15152	17497	2490
4.15-5.12	0.96	38-42	4	16851	67427	20365	14114	16298	2319
5.12-6.00	0.88	42-45.4	3.4	15688	53357	16115	11168	12897	1835
6-9	3	45.4-55.8	10.4	14270	148460	44839	31075	35886	5106
9-12		55.8-65.19	9.39	14315	134466	40613	28146	32503	4625
12-15		65.19-73.50	8.31	14948	124257	37529	26009	30036	4274
15-18		73.50-80.90	7.40	15434	115724	34952	24223	27973	3980
18-21		80.90-87.63	6.73	15749	106025	32023	22193	25629	3647
21-24		87.63-93.75	6.12	15906	97376	29411	20383	23538	3349
24-27		93.75-99.40	5.65	15920	89978	27176	18834	21750	3095
27-30		99.40-104.6	5.20	15826	82324	24864	17232	19899	2832
30-33		104.6-109.4	4.80	15598	74896	22621	15677	18104	2576
33-36		109.4-113.9	4.50	15199	68420	20665	14321	16538	2353
36-39		113.9-118.3	4.40	12305	54161	16358	11337	13092	1863
39-42	3	118.3-122.6	4.30	6638	28553	8624	5977	6902	982
42-44.9	2.9	122.6-126.57	3.97	1814	7203	2176	1508	1741	248
			TOTAL		2018567	609670	422520	487930	69430

[a]The mass is indicated below the symbol for each specie.

Table 5b. Exhaust products released into atmosphere by space shuttle SRMs: Mission 3B (pounds per altitude band per flight)

Exhaust products[a]								
CO_2	H_2O		H_2	N_2	$FeCl_2$	Cl	Fe	H
0.4141894	0.0942778	0.2822035	0.0208249	0.0874651	0.00594356	0.0028753	0.000155655	0.000205127
Burned	Exit	Burned	Exit					
17019	3874	11596	856	3594	244	118	6	8.4
17021	3874	11597		3594				
17022	3875	11598		3595				
17025	3875	11600		3595				
17027	3876	11601		3596				
17028	3876	11602		3596				
17031	3877	11604		3596				
17032	3877	11605		3597				
17034	3877	11606	856	3597				
17036	3878	11608	857	3598	244	118	6	8.4
34078	7757	23219	1713	7196	489	237	13	17
34087	7759	23225	1714	7198	489	237	13	17
16788	3821	11438	844	3545	241	117	6	8.3
32037	7292	21828	1611	6765	460	222	12	16
29982	6824	20428	1507	6331	430	208	11	15
27928	6357	19028	1404	5898	401	194	10	14
22100	5030	15058	1111	4667	317	153	8	11
61491	13997	41896	3092	12985	882	427	23	30
55695	12677	37947	2800	11761	799	387	21	28
51466	11715	35066	2588	10868	738	357	19	25
47932	10910	32658	2410	10122	688	333	18	24
43915	9996	29921	2208	9274	630	305	17	22
40333	9180	27480	2028	8517	579	280	15	20
37268	8483	25392	1874	7870	535	259	14	18
34098	7761	23232	1714	7200	489	237	13	17
31021	7061	21136	1560	6551	445	215	12	15
28339	6450	19308	1425	5984	407	197	11	14
22433	5106	15284	1128	4737	322	156	8	11
11826	2692	8058	595	2497	170	82	4	6
2983	679	2033	150	630	43	21	1	1
836070	190310	569650	42037	176560	19998	5804	314	414

Altitude band, km	Δ altitude, km	Time, s	Δtime, s	Average mass flow, 10^3 kg/s	Mass, 10^3 kg	Exhaust products[a]			
						Al_2O_3	HCl	CO	CO_2
						0.302028	0.209315	0.241719	0.0343946
								Exit	Exit
0-0.0095	0.0095	0-2	2	9.444	18.88	5.704	3.953	4.565	0.6495
0.0095-0.039	0.0295	2-4		9.446	18.89	5.704	3.953	4.565	0.6496
0.039-0.087	0.048	4-6		9.446		5.705	3.954	4.566	0.6496
0.087-0.160	0.073	6-8		9.447		5.705	3.954	4.566	0.6497
0.16-0.25	0.090	8-10	2	9.448	18.89	5.706	3.953	4.566	0.6498
0.25-0.50	0.250	10-14	4	9.449	37.79	11.41	7.912	9.134	1.300
0.50-0.85	0.35	14-18		9.451	37.79	11.41	7.911	9.136	
0.85-1.3	0.45	18-22		9.451	37.80	11.42	7.912	9.137	
1.3-1.9	0.60	22-26	4	9.454	37.81	11.42	7.914	9.139	1.300
1.9-2.2	0.30	26-28	2	9.445	18.89	5.704	3.953	4.565	0.6496
2.2-2.5	0.30	28-30	2	9.292	18.58	5.612	3.889	4.491	0.6390
2.5-3.3	0.80	30-34	4	8.859	35.43	10.70	7.416	8.564	1.219
3.3-4.2	0.90	34-38		8.282	33.12	10.00	6.933	8.006	1.139
4.2-5.1	0.90	38-42	4	7.705	30.81	9.307	6.450	7.448	1.060
5.1-6.0	0.90	42-45.44	3.44	7.123	24.50	7.399	5.128	5.921	0.8426
6-9	3	45.44-56.06	10.62	6.526	69.29	20.93	14.50	16.75	2.383
9-12		56.06-65.52	9.46	6.630	62.70	18.94	13.12	15.16	2.157
12-15		65.52-74.01	8.49	6.925	58.78	17.75	12.30	14.21	2.021
15-18		74.01-81.64	7.63	7.147	54.52	16.47	11.41	13.18	1.875
18-21		81.64-88.70	7.06	7.270	51.32	15.50	10.74	12.40	1.765
21-24		88.70-94.90	6.20	7.320	45.37	13.70	9.497	10.97	1.561
24-27		94.90-100.8	5.90	7.298	43.05	13.00	9.011	10.41	1.481
27-30		100.8 -106.2	5.40	7.227	39.02	11.78	8.167	9.431	1.342
30-33		106.2 -111.2	5.00	7.089	35.44	10.70	7.417	8.565	1.219
33-36		111.2 -116.08	4.88	6.230	30.40	9.180	6.362	7.347	1.045
36-39	3	116.08-120.80	4.72	3.227	15.24	4.602	3.189	3.680	0.5241
39-41.6	2.6	120.80-124.85	4.05	0.8686	3.519	1.063	0.7366	0.8506	0.1210
			TOTAL		915.6	276.5	191.6	221.3	31.49

[a]The mass is indicated below the symbol for each specie.

Table 5c. Exhaust products released into atmosphere by space shuttle SRMs: Mission 2 (metric tons per altitude band per flight)

Exhaust products[a]								
CO_2	H_2O		H_2	N_2	$FeCl_2$	Cl	Fe	H
0.4141894	0.0942778	0.2822035	0.0208249	0.0874651	0.00594356	0.0028753	0.000155655	0.000205127
Burned	Exit	Burned	Exit					
7.822	1.780	5.329	0.3933	1.652	0.1122	0.0543	2.939 E-3	3.874 E-3
7.823	1.781	5.330	0.3933		0.1123		2.940	3.874
7.823		5.330	0.3933				2.940	3.874
7.824		5.331	0.3934				2.940	3.875
7.825	1.781	5.331	0.3934	1.652	0.1123	0.0543	2.941	3.875
15.65	3.563	10.66	0.7869	3.305	0.2246	0.1087	5.882	7.751
15.65	3.563	10.67	0.7871	3.306	0.2246	0.1087	5.883	7.753
15.66	3.564	10.67	0.7872	3.306	0.2247	0.1087	5.884	7.754
15.66	3.564	10.67	0.7873	3.307	0.2247	0.1087	5.885	7.755
7.822	1.781	5.330	0.3933	1.652	0.1123	0.0543	2.940	3.874
7.695	1.752	5.243	0.3869	1.625	0.1104	0.0534	2.892	3.811
14.67	3.340	9.998	0.7378	3.099	0.2106	0.1019	5.515	7.267
13.72	3.123	9.347	0.6897	2.897	0.1969	0.0952	5.155	6.794
12.76	2.905	8.696	0.6417	2.695	0.1831	0.0886	4.796	6.321
10.15	2.310	6.913	0.5101	2.143	0.1456	0.0704	3.813	5.025
28.70	6.532	19.55	1.443	6.060	0.4118	0.1992	10.785	14.213
25.97	5.912	17.70	1.306	5.484	0.3727	0.1803	9.760	12.861
24.35	5.542	16.59	1.224	5.141	0.3494	0.1690	9.150	12.057
22.58	5.140	15.39	1.135	4.768	0.3240	0.1568	8.486	11.184
21.25	4.838	14.48	1.069	4.488	0.3050	0.1476	7.988	10.527
18.79	4.278	12.80	0.9449	3.968	0.2697	0.1305	7.062	9.307
17.83	4.058	12.15	0.8965	3.765	0.2559	0.1238	6.701	8.830
16.16	3.678	11.01	0.8125	3.413	0.2319	0.1122	6.073	8.004
14.68	3.341	10.00	0.7379	3.099	0.2106	0.1019	5.516	7.269
12.59	2.866	8.578	0.6330	2.659	0.1807	0.0874	4.731	6.235
6.311	1.437	4.300	0.3173	1.333	0.0906	0.0438	2.372 E-3	3.126 E-3
1.458	0.3318	0.9931	0.0733	0.3078	0.0209	0.0101	5.477 E-4	7.218 E-4
379.2	86.32	258.4	19.07	80.08	5.442	2.633	0.1425	0.1878

Altitude band, km	Δaltitude, km	Time, s	Δtime, s	Average mass flow, 10^3 lb/s	Mass, 10^3 lb	Exhaust products[a]			
						Al_2O_3	HCl	CO	CO_2
						0.302028	0.209315	0.241719	0.0343946
								Exit	Exit
0-0.0095	0.0095	0-2	2	20821	41633	12574	8714	10064	1432
0.0095-0.039	0.0295	2-4		20824	41639	12576	8716	10065	
0.039-0.087	0.048	4-6		20825	41641	12577	8716	10065	
0.087-0.160	0.073	6-8		20827	41645	12578	8717	10066	1432
0.16-0.25	0.090	8-10	2	20829	41649	12579	8718	10067	1433
0.25-0.50	0.250	10-14	4	20832	83310	25162	17438	20138	2865
0.50-0.85	0.35	14-18		20835	83322	25166	17440	20141	2866
0.85-1.3	0.45	18-22		20835	83333	25169	17443	20143	2866
1.3-1.9	0.60	22-26	4	20842	83350	25174	17446	20147	2867
1.9-2.2	0.30	26-28	2	20823	41637	12576	8715	10065	1432
2.2-2.5	0.30	28-30	2	20485	40961	12371	8573	9901	1409
2.5-3.3	0.80	30-34	4	17531	78107	23591	16349	18880	2686
3.3-4.2	0.90	34-38		18259	73020	22054	15284	17650	2511
4.2-5.1	0.90	38-42	4	16987	67933	20518	14219	16421	2337
5.1-6.0	0.90	42-45.44	3.44	15703	54006	16311	11304	13054	1858
6-9	3	45.44-56.06	10.62	14387	152757	46137	31974	36924	5254
9-12		56.06-65.52	9.46	14616	138237	41751	28935	33415	4755
12-15		65.52-74.01	8.49	15268	129596	39142	27126	31326	4457
15-18		74.01-81.64	7.63	15756	120191	36301	25158	29052	4134
18-21		81.64-88.70	7.06	16028	113133	34169	23680	27346	3891
21-24		88.70-94.90	6.20	16137	100027	30211	20937	24178	3440
24-27		94.90-100.8	5.9	16089	94905	28664	19865	22940	3264
27-30		100.8 -106.2	5.40	15933	86019	25980	18005	20792	2959
30-33		106.2 -111.2	5.00	15628	78121	23595	16352	18883	2687
33-36		111.2 -116.08	4.88	13735	67012	20240	14027	16198	2305
36-39	3	116.08-120.80	4.72	7115	33593	10146	7032	8120	1155
39-41.6	2.6	120.80-124.85	4.05	1915	7758	2343	1624	1875	267
			TOTAL		2018534	609650	422510	487920	69426

[a]The mass is indicated below the symbol for each specie.

Table 5d. Exhaust products released into atmosphere by space shuttle SRMs: Mission 2 (pounds per altitude band per flight)

Exhaust products[a]								
CO_2	H_2O		H_2	N_2	$FeCl_2$	Cl	Fe	H
0.4141894	0.0942778	0.2822035	0.0208249	0.0874651	0.00594356	0.0028753	0.000155655	0.000205127
Burned	Exit	Burned	Exit					
17244	3925	11749	867	3641	247	120	6	9
17246	3926	11751		3642	247			
17247	3926	11751		3642	247			
17249	3926	11752		3642	248			
17250	3927	11754	867	3643	248	120	6	9
34506	7854	23510	1735	7287	495	240	13	17
34511	7855	23514	1735	7288				
34516	7856	23517	1735	7289				
34523	7858	23522	1736	7290	495	240	13	17
17246	3925	11750	867	3642	247	120	6	9
16966	3862	11559	853	3583	243	118	6	8
32351	7364	22042	1627	6832	464	225	12	16
30244	6884	20607	1521	6387	434	210	11	15
28137	6405	19171	1415	5942	404	195	11	14
22369	5092	15241	1125	4724	321	155	8	11
63270	14402	43109	3181	13361	908	439	24	31
57256	13033	39011	2879	12091	822	397	22	28
53677	12218	36572	2699	11335	770	373	20	27
49782	11331	33918	2503	10513	714	346	19	25
46859	10665	31927	2356	9895	672	325	18	23
41430	9430	28228	2083	8749	595	288	16	21
39309	8947	26783	1976	8301	564	273	15	19
35628	8110	24275	1791	7524	511	247	13	18
32357	7365	22046	1627	6833	464	225	12	16
27756	6318	18911	1396	5861	398	193	10	14
13914	3167	9480	700	2938	200	97	5	7
3213	731	2189	162	679	46	22	1	2
836060	190300	569640	42036	176550	11997	5804	314	414

Table 6. Exit plane mass fraction of species from main engine[a, b]

Species	Mass fractions
H_2O	9.5939×10^{-1}
H_2	3.547×10^{-2}
Ar	4.71×10^{-3}
N_2	3.065×10^{-4}
H	8.545×10^{-5}
OH	3.439×10^{-5}
O_2	2.029×10^{-6}
O	1.635×10^{-7}

[a]The first four species account for 99.99% of the flow.

[b]Ar and N_2 are impurities in the O_2.

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Table 7a. Orbiter engine H_2 and H_2O production during launch and sum of SRM and orbiter engine H_2O production: Mission 3B (metric tons per altitude band per flight)

Altitude band, km	Δ altitude, km	Time, s	Δ time, s	Orbiter mass injected, 10^3 kg	Production[a]: Orbiter engine H_2O 0.9594 Exit	Production[a]: Orbiter engine H_2O 1.2778 Burned	Production[a]: Orbiter engine H_2[b] 0.03547 Exit	Production[a]: SRM + Orbiter H_2O Exit	Production[a]: SRM + Orbiter H_2O Burned
0-0.0095	0.0095	0-2	2	0.9317	0.894	1.191	0.0330	2.65	6.45
0.0095-0.038	0.0285	2-4							
0.038-0.088	0.050	4-6							
0.088-0.160	0.072	6-8							
0.16-0.25	0.090	8-10							
0.25-0.36	0.11	10-12							
0.36-0.50	0.14	12-14							
0.50-0.66	0.16	14-16							
0.66-0.84	0.18	16-18							
0.84-1.06	0.22	18-20	2	0.9317	0.894	1.191	0.0330	2.65	6.45
1.06-1.55	0.49	20-24	4	1.863	1.787	2.380	0.0661	5.30	12.91
1.55-2.16	0.61	24-28	4	1.863	1.787	2.380	0.0661	5.30	12.91
2.16-2.51	0.35	28-30	2	0.9317	0.894	1.191	0.0330	2.63	6.38
2.51-3.28	0.77	30-34	4	1.863	1.787	2.380	0.0661	5.09	12.28
3.28-4.15	0.87	34-38		1.863	1.787	2.380	0.0661	4.88	11.65
4.15-5.12	0.96	38-42	4	1.863	1.787	2.380	0.0661	4.67	11.01
5.12-6.00	0.88	42-45.4	3.4	1.584	1.519	2.023	0.0562	3.80	8.85
6-9	3	45.4-55.8	10.4	4.844	4.647	6.190	0.1728	10.99	25.19
9-12		55.8-65.19	9.39	4.374	4.196	5.589	0.1551	9.94	22.80
12-15		65.19-73.50	8.31	3.871	3.713	4.946	0.1373	9.03	20.86
15-18		73.50-80.90	7.40	3.446	3.307	4.404	0.1222	8.26	19.21
18-21		80.90-87.63	6.73	3.134	3.007	4.005	0.1112	7.54	17.57
21-24		87.63-93.75	6.12	2.850	2.735	3.642	0.1011	6.89	16.10
24-27		93.75-99.40	5.65	2.631	2.524	3.362	0.0933	6.37	14.88
27-30		99.40-104.6	5.20	2.422	2.323	3.095	0.0860	5.84	13.63
30-33		104.6-109.4	4.80	2.236	2.145	2.857	0.0790	5.35	12.44
33-36		109.4-113.9	4.50	2.096	2.011	2.678	0.0743	4.94	11.43
36-39		113.9-118.3	4.40	2.049	1.966	2.619	0.0727	4.28	9.55
39-42		118.3-122.6	4.30	2.003	1.921	2.559	0.0710	3.14	6.21
42-45	3	122.6-126.7	4.10	1.910	1.832	2.440	0.0677	2.14	3.36

SRM burnout

45-48	3	126.70-131.09	4.39	2.045	1.962	2.613	0.0725
48-51		131.09-135.50	4.41	2.054	1.971	2.624	
51-54		135.50-139.92	4.42	2.058	1.975	2.630	
54-57		139.92-144.35	4.43	2.063	1.980	2.637	0.0725
57-60		144.35-149.05	4.70	2.189	2.100	2.797	0.0776
60-63		149.05-153.76	4.71	2.194	2.105	2.803	0.0776
63-66		153.76-158.46	4.70	2.189	2.100		0.0778
66-69		158.46-163.38	4.92	2.292	2.199		0.0813
69-72		163.38-168.40	5.00	2.329	2.234		0.0836
72-75		168.40-173.43	5.03	2.343	2.248		0.0830
75-78		173.43-178.62	5.19	2.417	2.319		0.0857
78-81		178.62-183.98	5.36	2.497	2.395		0.0885
81-84		183.98-189.35	5.37	2.501	2.400		0.0887
84-87		189.35-194.90	5.55	2.585	2.480		0.0917
87-90		194.90-200.64	5.74	2.674	2.565		0.0948
90-93		200.64-206.37	5.70	2.655	2.547		0.0942
93-96		206.37-212.40	6.03	2.809	2.695		0.0996
96-99		212.40-218.55	6.15	0.811	2.748		0.1020
99-102		218.55-224.74	6.19	4.937	2.766		0.1020
102-105		224.74-231.32	6.58	3.065	2.940		0.1087
105-108		231.32-237.91	6.59	3.070	2.945		0.1089
108-111		237.91-244.82	6.91	3.218	3.088		0.1141
111-114		244.82-251.90	7.08	3.298	3.164		0.1170
114-117		251.90-259.19	7.29	3.395	3.257		0.1204
117-120		259.19-266.79	7.60	3.540	3.396		0.1256
120-123		266.79-274.58	7.79	3.628	3.481		0.1287
123-126		274.58-282.76	8.18	3.810	3.655		0.1351
126-129		282.76-291.19	8.43	3.926	3.767		0.1393
129-132		291.19-300.03	8.84	4.117	3.950		0.1460
132-135		300.03-309.27	9.24	4.304	4.129		0.1526
135-138		309.27-318.83	9.56	4.453	4.272		0.1579
138-141		318.83-329.11	10.28	4.788	4.594		0.1698
141-144		329.11-339.80	10.69	4.979	4.777		0.1766
144-147		339.80-351.10	11.30	5.263	5.049		0.1867
147-150		351.10-363.38	12.28	5.719	5.487		0.2029
150-153		363.38-376.51	13.13	6.115	5.867		0.2169
153-156		376.51-390.75	14.24	6.633	6.363		0.2353
156-159		390.75-406.45	15.70	7.312	7.016		0.2594
159-162		406.45-424.12	17.67	8.230	7.896		0.2919
162-165		424.12-444.58	20.46	9.359	8.979		0.3319
165-168		444.58-471.85	27.27	10.35	9.934		0.3673
168-170.09	3	471.85-511.90	40.05	12.79	12.27		0.4537
			TOTAL	230.0	220.68	90.51	8.160

[a]The mass is indicated below the symbol for each specie.

[b]Exit H_2 will be converted to H_2O by afterburning which ceases at some altitude between 45 and 60 km.

Table 7b. Orbiter engine H_2 and H_2O production during launch and sum of SRM and orbiter engine H_2O production: Mission 3B (pounds per altitude band per flight)

Altitude band, km	Δ altitude, km	Time, s	Δ time, s	Orbiter mass injected, 10^3 lb	Production[a]: Orbiter engine H_2O 0.9594 Exit	Orbiter engine H_2O 1.2778 Burned	Orbiter engine H_2[b] 0.03547 Exit	SRM + Orbiter H_2O Exit	SRM + Orbiter H_2O Burned
0-0.0095	0.0095	0-2	2	2053.6	1971	2625	72.86	5844	14217
0.0095-0.038	0.0285	2-4						5844	14218
0.038-0.088	0.050	4-6						5844	14219
0.088-0.160	0.072	6-8						5845	14221
0.16-0.25	0.090	8-10						5845	14222
0.25-0.36	0.11	10-12						5846	14223
0.36-0.50	0.14	12-14						5846	14225
0.50-0.66	0.16	14-16						5847	14226
0.66-0.84	0.18	16-18						5847	14227
0.84-1.06	0.22	18-20	2	2053.6	1971	2625	72.86	5848	14229
1.06-1.55	0.49	20-24	4	4107.2	3940	5248	145.7	11694	28459
1.55-2.16	0.61	24-28	4	4107.2	3940	5248	145.7	11696	28464
2.16-2.51	0.35	28-30	2	2053.6	1971	2625	72.86	5791	14059
2.51-3.28	0.77	30-34	4	4107.2	3940	5248	145.7	11230	27068
3.28-4.15	0.87	34-38		4107.2	3940	5248	145.7	10762	7288
4.15-5.12	0.96	38-42	4	4107.2	3940	5248	145.7	10295	24270
5.12-6.00	0.88	42-45.4	3.4	3491	3349	4461	123.8	8378	19514
6-9	3	45.4-55.8	10.4	10679	10245	13646	378.8	24237	55527
9-12		55.8-65.19	9.39	9642	9251	12320	342.0	21924	50254
12-15		65.19-73.50	8.31	8533	8187	10904	302.7	19907	45986
15-18		73.50-80.90	7.40	7598	7289	9709	269.5	18204	42355
18-21		80.90-87.63	6.73	6910	6629	8830	245.1	16621	38740
21-24		87.63-93.75	6.12	6284	6029	8030	222.9	15206	35500
24-27		93.75-99.40	5.65	5801	5565	7413	205.8	14045	32796
27-30		99.40-104.6	5.20	5339	5122	6822	189.4	12881	30046
30-33		104.6-109.4	4.80	4929	4729	6298	174.8	11788	27427
33-36		109.4-113.9	4.50	4621	4433	5905	163.9	10881	25207
36-39		113.9-118.3	4.40	4518	4335	5773	160.3	9439	21052
39-42		118.3-122.6	4.30	4415	4236	5641	156.6	6927	13696
42-45	3	122.6-126.7	4.10	4210	4039	5380	149.3	4718	7412

SRM burnout

45-48	3	126.70-131.09	4.39	4508	4325	5760	159.9
48-51		131.09-135.50	4.41	4528	4344	5786	160.6
51-54		135.50-139.92	4.42	4538	4354	5799	160.9
54-57		139.92-144.35	4.43	4549	4364	5813	161.4
57-60		144.35-149.05	4.70	4826	4630	6167	171.2
60-63		149.05-153.76	4.71	4836	4639	6179	171.5
63-66		153.76-158.46	4.70	4826	4630		171.2
66-69		158.46-163.38	4.92	5052	4847		179.2
69-72		163.38-168.40	5.00	5134	4926		182.1
72-75		168.40-173.43	5.03	5165	4955		183.2
75-78		173.43-178.62	5.19	5329	5113		189.0
78-81		178.62-183.98	5.36	5504	5281		195.2
81-84		183.98-189.35	5.37	5514	5290		195.6
84-87		189.35-194.90	5.55	5699	5468		202.1
87-90		194.90-200.64	5.74	5894	5655		209.1
90-93		200.64-206.37	5.70	5853	5615		207.6
93-96		206.37-212.40	6.03	6192	5941		219.6
96-99		212.40-218.55	6.15	6315	6059		224.0
99-102		218.55-224.74	6.19	6356	6098		225.4
102-105		224.74-231.32	6.58	6756	6482		239.6
105-108		231.32-237.91	6.59	6767	6492		240.0
108-111		237.91-244.82	6.91	7095	6807		251.7
111-114		244.82-251.90	7.08	7270	6975		257.9
114-117		251.90-259.19	7.29	7485	7181		265.5
117-120		259.19-266.79	7.60	7804	7487		276.8
120-123		266.79-274.58	7.79	7999	7674		283.7
123-126		274.58-282.76	8.18	8399	8058		297.9
126-129		282.76-291.19	8.43	8656	8305		307.0
129-132		291.19-300.03	8.84	9077	8708		322.0
132-135		300.03-309.27	9.24	9488	9103		336.5
135-138		309.27-318.83	9.56	9816	9417		348.2
138-141		318.83-329.11	10.28	10556	10127		374.4
141-144		329.11-339.80	10.69	10976	10530		389.3
144-147		339.80-351.10	11.30	11603	11132		411.6
147-150		351.10-363.38	12.28	12609	12097		447.2
150-153		363.38-376.51	13.13	13482	12935		478.2
153-156		376.51-390.75	14.24	14622	14028		518.6
156-159		390.75-406.45	15.70	16121	15467		571.8
159-162		406.45-424.12	17.67	18144	17407		643.6
162-165		424.12-444.58	20.46	20632	19794		731.8
165-168		444.58-471.85	27.27	22828	21902		809.7
168-170.09	3	471.85-511.90	40.05	28196	27051		1000
			TOTAL	507097	486510	201741	17987

[a]The mass is indicated below the symbol for each specie.

[b]Exit H_2 will be converted to H_2O by afterburning which ceases at some altitude between 150,000 and 200,000 ft.

Table 7c. Orbiter engine H_2 and H_2O production and sum of SRM and orbiter engine H_2O production: Mission 2 (metric tons per altitude band per flight)

Altitude band, km	Δ altitude, km	Time, s	Δ time, s	Orbiter mass injected, 10^3 kg	Production[a] Orbiter engine H_2O 0.9594 Exit	Production[a] Orbiter engine H_2O 1.2778 Burned	Production[a] Orbiter engine H_2[b] 0.03547 Exit	Production[a] SRM + Orbiter H_2O Exit	Production[a] SRM + Orbiter H_2O Burned
0-0.0095	0.0095	0-2	2	0.9317	0.894	1.191	0.033	2.67	6.52
0.0095-0.039	0.0295	2-4							
0.039-0.087	0.048	4-6							
0.087-0.160	0.073	6-8							
0.16-0.25	0.090	8-10	2	0.9317	0.894	1.191	0.033	2.67	6.52
0.25-0.50	0.250	10-14	4	1.863	1.787	2.380	0.066	5.35	13.05
0.50-0.85	0.35	14-18							
0.85-1.3	0.45	18-22							
1.3-1.9	0.60	22-26	4	1.863	1.787	2.380	0.066	5.35	13.05
1.9-2.2	0.30	26-28	2	0.9317	0.894	1.191	0.033	2.67	6.52
2.2-2.5	0.30	28-30	2	0.9317	0.894	1.191	0.033	2.65	6.52
2.5-3.3	0.80	30-34	4	1.863	1.787	2.380	0.066	5.12	12.38
3.3-4.2	0.90	34-38		1.863	1.787	2.380	0.066	4.91	11.73
4.2-5.1	0.90	38-42	4	1.863	1.787	2.380	0.066	4.69	11.08
5.1-6.0	0.90	42-45.44	3.44	1.602	1.537	2.047	0.057	3.85	8.96
6-9	3	45.44-56.06	10.62	4.947	4.746	6.321	0.175	11.28	25.88
9-12		56.06-65.52	9.46	4.406	4.227	5.630	0.156	10.14	23.33
12-15		65.52-74.01	8.49	3.954	3.794	5.053	0.140	9.34	21.65
15-18		74.01-81.64	7.63	3.554	3.409	4.541	0.126	8.55	19.93
18-21		81.64-88.70	7.06	3.288	3.155	4.202	0.117	7.99	18.68
21-24		88.70-94.90	6.20	2.888	2.770	3.690	0.102	7.04	16.50
24-27		94.90-100.8	5.90	2.748	2.636	3.511	0.097	6.70	15.66
27-30		100.8-106.2	5.40	2.515	2.413	3.214	0.089	6.09	14.23
30-33		106.2-111.2	5.00	2.329	2.234	2.976	0.083	5.58	12.98
33-36		111.2-116.08	4.88	2.273	2.180	2.904	0.081	5.04	11.48
36-39		116.08-120.8	4.72	2.198	2.109	2.809	0.078	3.55	7.11
39-42	3	120.8-125.5	4.70	2.189	2.100	2.797	0.078	2.43	3.79

SRM burnout

42-45	3	125.5-130.40	4.90	2.282	2.189	2.916	0.081
45-48		130.40-135.44	5.04	2.347	2.252	2.999	0.083
48-51		135.44-140.48	5.04	2.347	2.252	2.999	0.083
51-54		140.48-145.66	5.18	2.413	2.315	3.083	0.086
54-57		145.66-151.18	5.52	2.571	2.467	3.285	0.091
57-60		151.18-156.69	5.51	2.566	2.462	3.279	0.091
60-63		156.69-162.62	5.91	2.752	2.640	3.517	0.098
63-66		162.62-169.17	6.55	3.051	2.927		0.108
66-69		169.17-175.72	6.55	3.051	2.927		0.108
69-72		175.72-181.85	6.13	2.855	2.739		0.101
72-75		181.85-187.95	6.10	2.841	2.726		0.101
75-78		187.95-194.48	6.53	3.041	2.918		0.108
78-81		194.48-201.84	7.36	3.428	3.289		0.122
81-84		201.84-209.31	7.47	3.479	3.338		0.123
84-87		209.31-217.40	8.09	3.768	3.615		0.134
87-90		217.40-225.57	8.17	3.805	3.651		0.135
90-93		225.57-234.12	8.55	3.982	3.820		0.141
93-96		234.12-243.25	9.13	4.253	4.080		0.151
96-99		243.25-253.65	10.4	4.844	4.647		0.172
99-102		253.65-264.41	10.76	5.011	4.808		0.178
102-105		264.41-275.74	11.33	5.277	5.063		0.187
105-108		275.74-288.04	12.30	5.729	5.496		0.203
108-111		288.04-302.01	13.97	6.506	6.242		0.231
111-114		302.01-322.06	20.05	9.338	8.959		0.331
114-117	3	322.06-351.01	28.95	13.48	12.936		0.478
117-119[c]	2	351.01-509.30	158.30	68.79	65.994		2.440
			TOTAL	232.3	222.834	96.77	8.238

[a]The mass is indicated below the symbol for each specie.

[b]Exit H_2 will be converted to H_2O by afterburning which ceases at some altitude between 45 and 60 km.

[c]Mass flow decreasing to burnout.

Table 7d. Orbiter engine H_2 and H_2O production during launch and sum of SRM and orbiter engine H_2O production: Mission 2 (pounds per altitude band per flight)

Altitude band, km	Δ altitude, km	Time, s	Δ time, s	Orbiter mass injected, 10^3 lb	Production[a]: Orbiter engine H_2O 0.9594 Exit	Orbiter engine H_2O 1.2778 Burned	Orbiter engine H_2[b] 0.03547 Exit	SRM + Orbiter H_2O Exit	SRM + Orbiter H_2O Burned
0-0.0095	0.0095	0-2	2	2054	1971.61	2625	72.86	5897	14377
0.0095-0.039	0.0295	2-4				2625		5897	14378
0.039-0.087	0.048	4-6				2624		5897	14379
0.087-0.160	0.073	6-8				2624		5898	14380
0.16-0.25	0.090	8-10	2	2054	1971.61	2624	72.86	5898	14381
0.25-0.50	0.250	10-14	4	4107	3940	5248	145.7	11796	28763
0.50-0.85	0.35	14-18				5248	145.7	11796	28767
0.85-1.3	0.45	18-22				5248	145.7	11797	28770
1.3-1.9	0.60	22-26	4	4107	3940	5248	145.6	11799	28775
1.9-2.2	0.30	26-28	2	2054	1971	2625	72.86	5897	14378
2.2-2.5	0.30	28-30	2	2054	1971	2625	72.86	5834	14379
2.5-3.3	0.80	30-34	4	4107	3940	5248	145.7	11305	27295
3.3-4.2	0.90	34-38		4107	3940	5248	145.7	10826	25859
4.2-5.1	0.90	38-42	4	4107	3940	5248	145.7	10346	24423
5.1-6.0	0.90	42-45.44	3.44	3532	3389	4513	125.3	8482	19757
6-9	3	45.44-56.06	10.62	10905	10462.3	1393	386.8	24867	57052
9-12		56.06-65.52	9.46	9714	9320	1241	344.6	22356	51432
12-15		65.52-74.01	8.49	8718	8364	11140	309.2	20585	47721
15-18		74.01-81.64	7.63	7834	7516	10010	277.9	18850	43936
18-21		81.64-88.70	7.06	7249	6955	9263	257.1	17623	41197
21-24		88.70-94.90	6.20	6366	6108	8134	225.8	1554	36368
24-27		94.90-100.8	5.90	6058	5812	7341	214.9	14761	34529
27-30		100.8-106.2	5.40	5545	5320	7085	196.7	13431	31365
30-33		106.2-111.2	5.00	5134	4926	6560	182.1	12293	28611
33-36		111.2-116.08	4.88	5011	4808	6403	177.7	11127	25318
36-39		116.08-120.8	4.72	4846	4649	6192	171.9	7817	15674
39-42	3	120.8-125.5	4.70	4826	4630	6167	171.2	5362	8357

SRM burnout

42-45	3	125.5-130.40	4.90	5031	4827	6429	178.5
45-48	↑	130.4-135.44	5.04	5175	4965	6613	183.6
48-51		135.44-140.48	5.04	5175	4965	6613	183.6
51-54		140.48-145.66	5.18	5319	5103	6797.62	188.7
54-57		145.66-151.18	5.52	5668	5438	7243.57	201.0
57-60		151.18-156.69	5.51	5658	5428	7230.79	200.7
60-63		156.69-162.62	5.91	6068	5822	7754	215.2
63-66		162.62-169.17	6.55	6726	6453		238.6
66-69		169.17-175.72	6.55	6726	6453		238.6
69-72		175.72-181.85	6.13	6294	6038		223.2
72-75		181.85-187.95	6.10	6263	6009		222.1
75-78		187.95-194.48	6.53	6705	6433		237.8
78-81		194.48-201.84	7.36	7557	7250		268.0
81-84		201.84-209.31	7.47	7670	7359		272.1
84-87		209.31-217.40	8.09	8307	7970		294.6
87-90		217.40-225.57	8.17	8389	8048		297.6
90-93		225.57-234.12	8.55	8779	8423		311.4
93-96		234.12-243.25	9.13	9375	8994		332.5
96-99		243.25-253.65	10.4	10679	10250		378.8
99-102		253.65-264.41	10.76	11048	10600		391.9
102-105		264.41-275.74	11.33	11634	11160		412.7
105-108		275.74-288.04	12.30	12630	12120		448.0
108-111		288.04-302.01	13.97	14344	13760		508.8
111-114	↓	302.01-322.06	20.05	20587	19750		730.2
114-117	3	322.06-351.01	28.95	29726	28520		1054
117-119[c]	2	351.01-509.30	158.30	151647	145500		5380
			TOTAL		491256	213342	18162.2

[a]The mass is indicated below the symbol for each specie.

[b]Exit H_2 will be converted to H_2O by afterburning which ceases at some altitude between 150,000 and 200,000 ft.

[c]Mass flow decreasing to burnout.

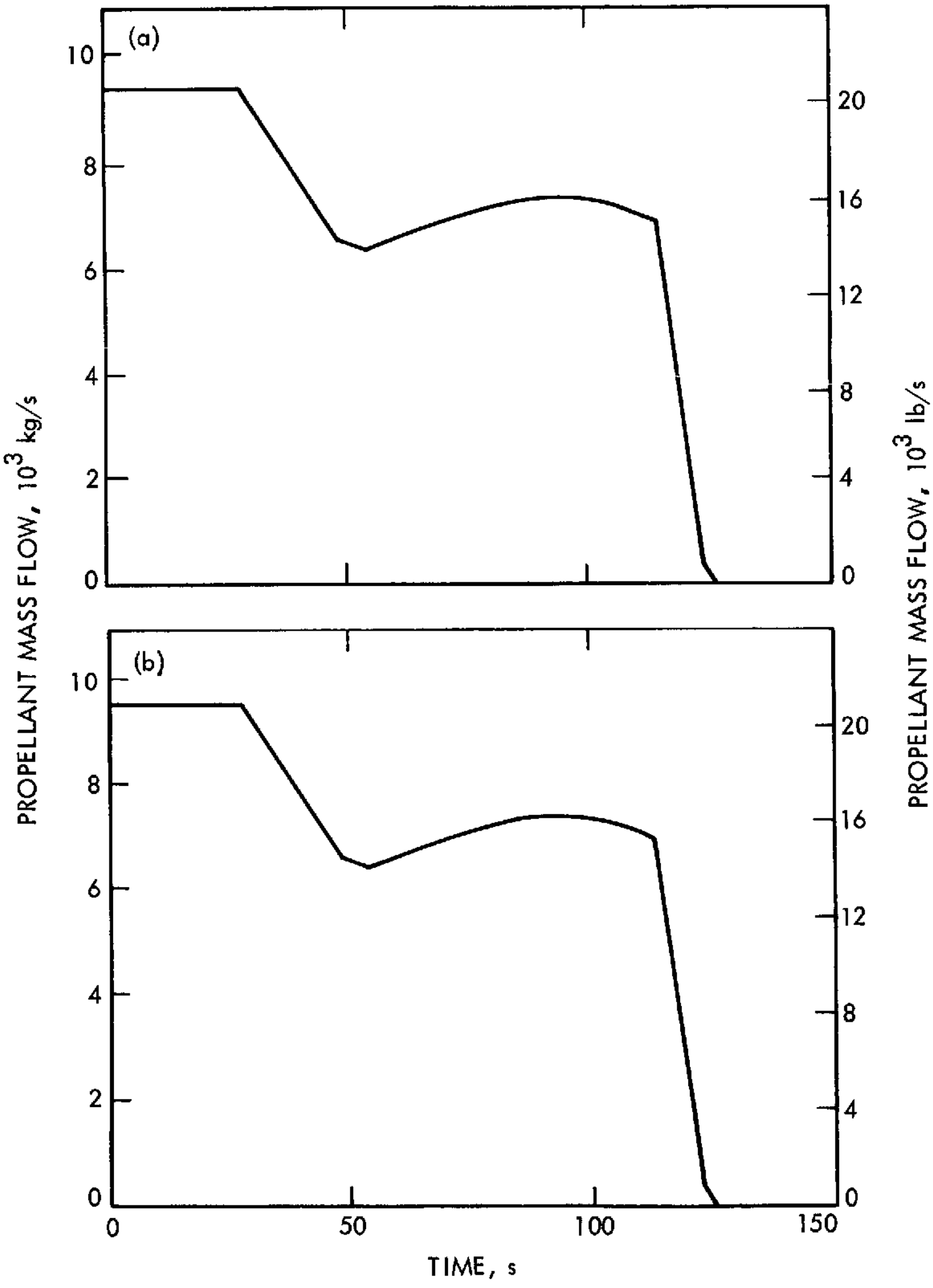

Fig. 1. Propellant mass flow (SRMs only): (a) Mission 3B, (b) Mission 2

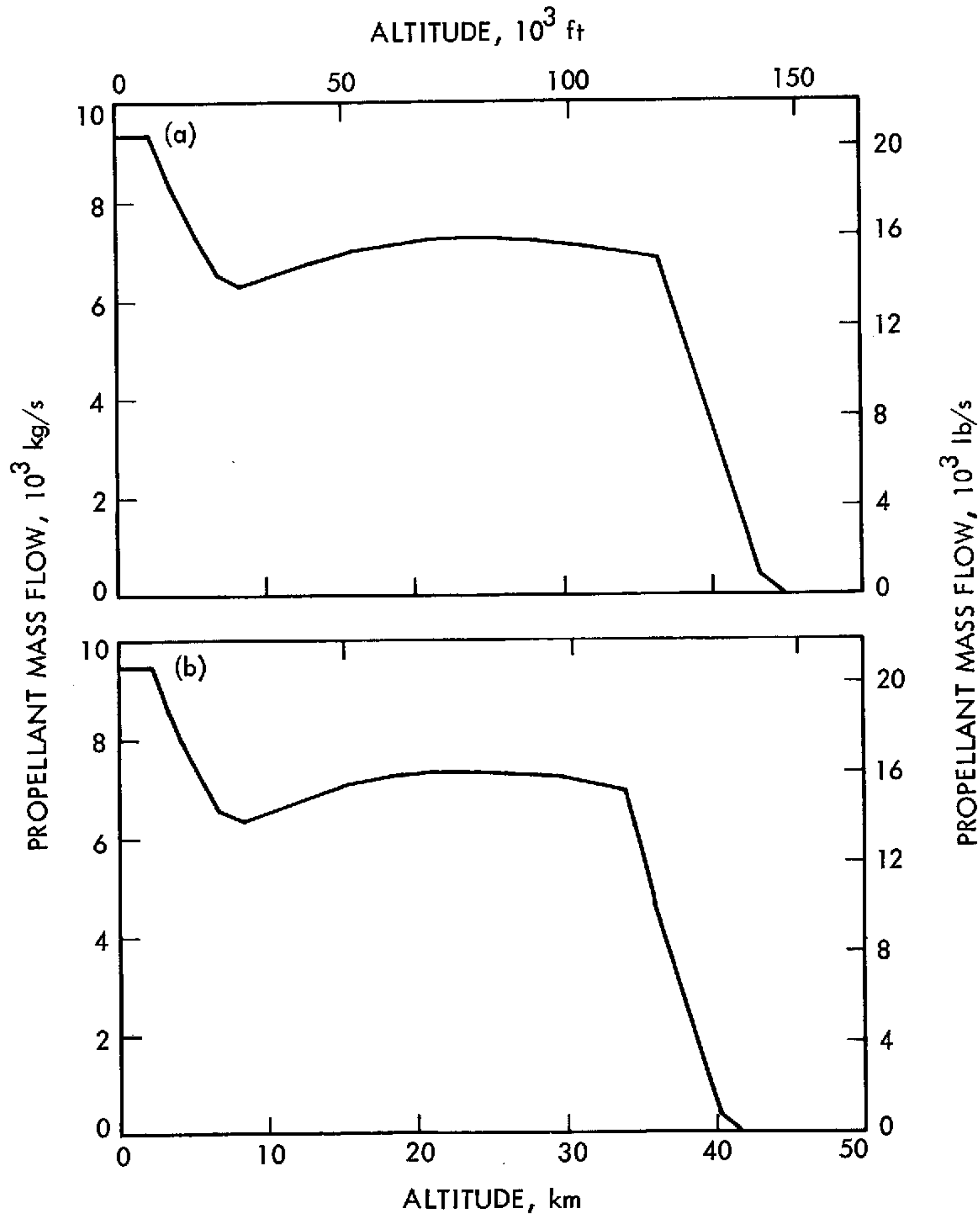

Fig. 2. Propellant mass flow versus altitude (SRMs only): (a) Mission 3B, (b) Mission 2

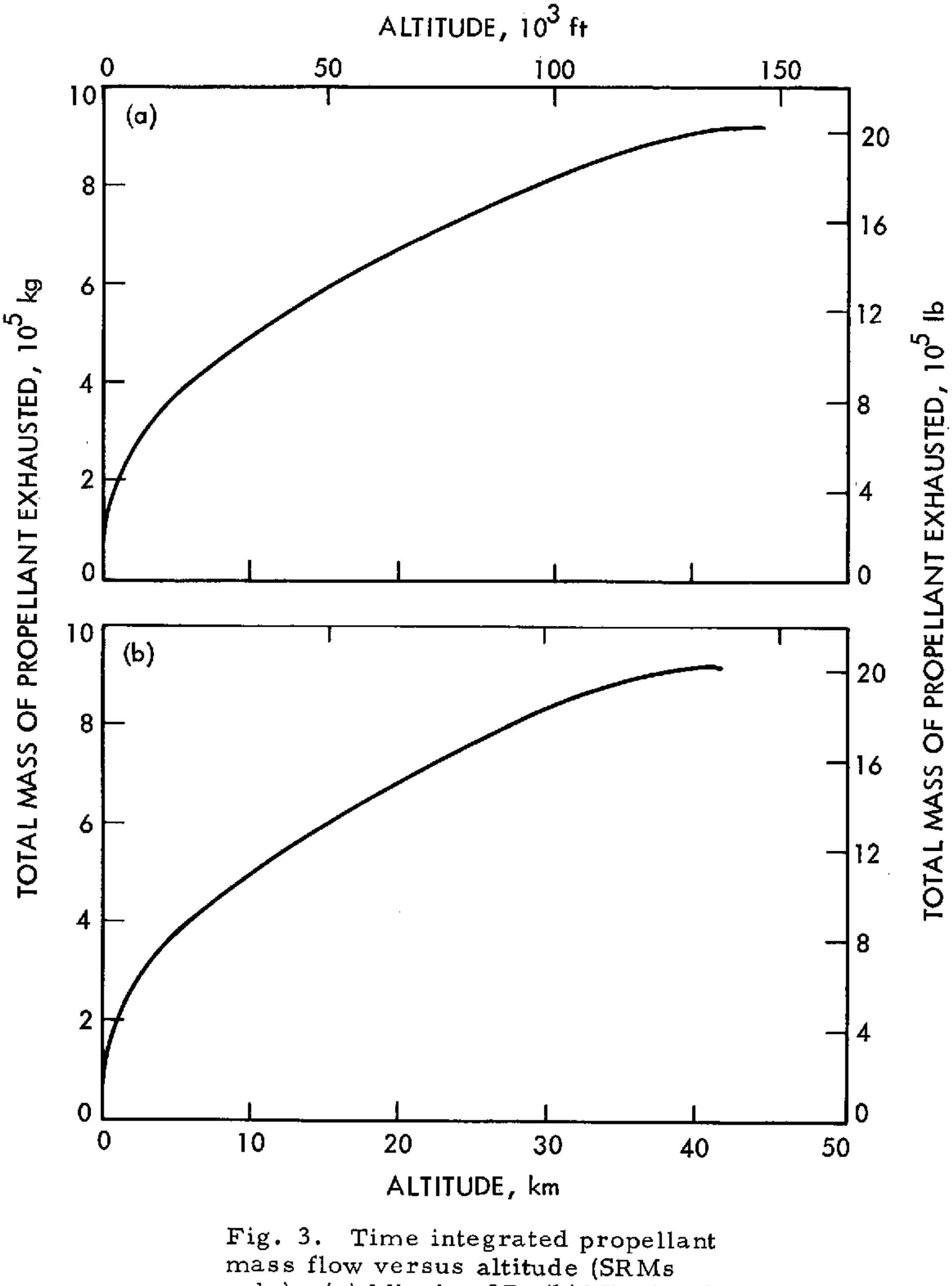

Fig. 3. Time integrated propellant mass flow versus altitude (SRMs only): (a) Mission 3B, (b) Mission 2

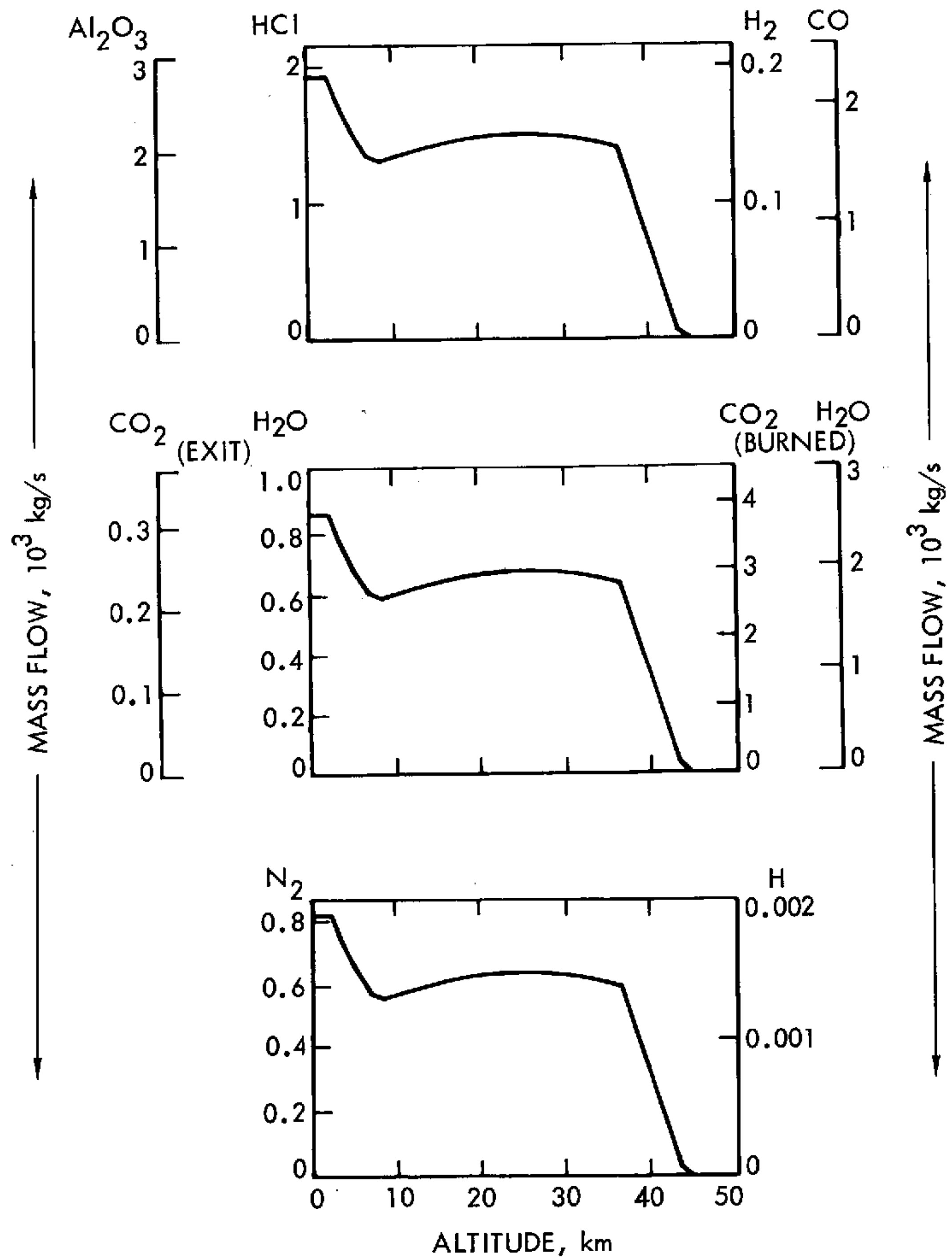

Fig. 4a. Production rate of indicated species (SRMs only): Mission 3B

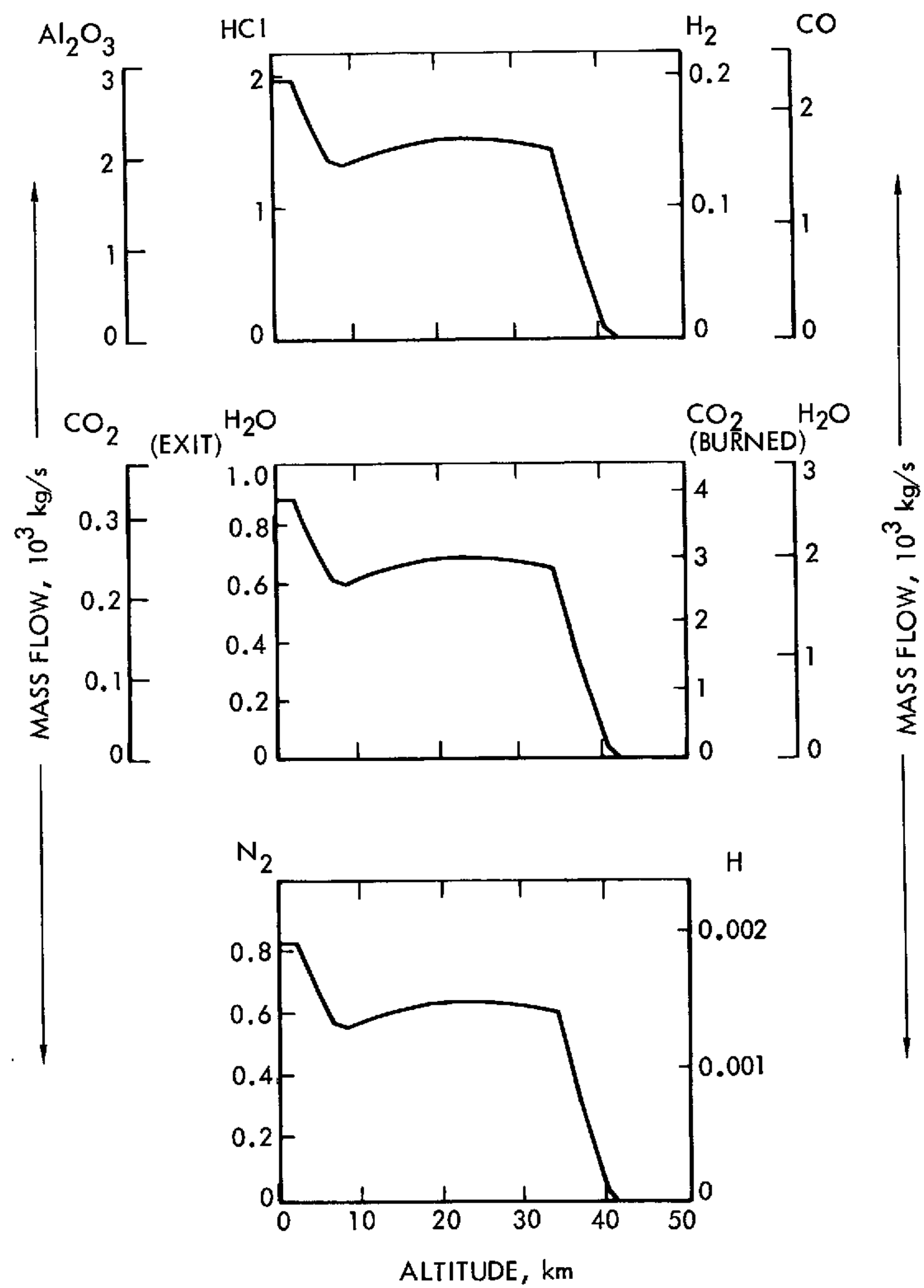

Fig. 4b. Production rate of indicated species (SRMs only): Mission 2

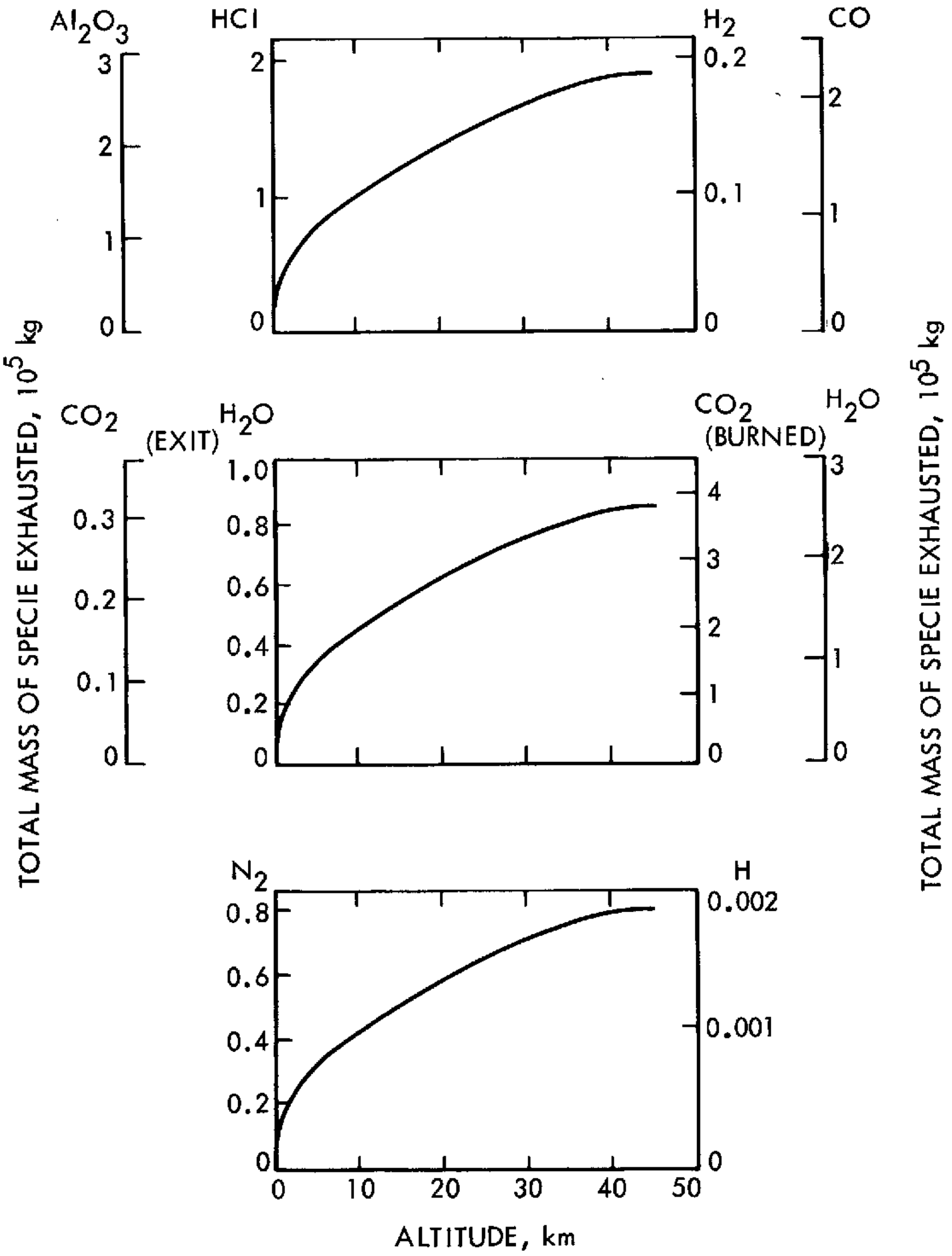

Fig. 5a. Total production of indicated species to given altitude: Mission 3B

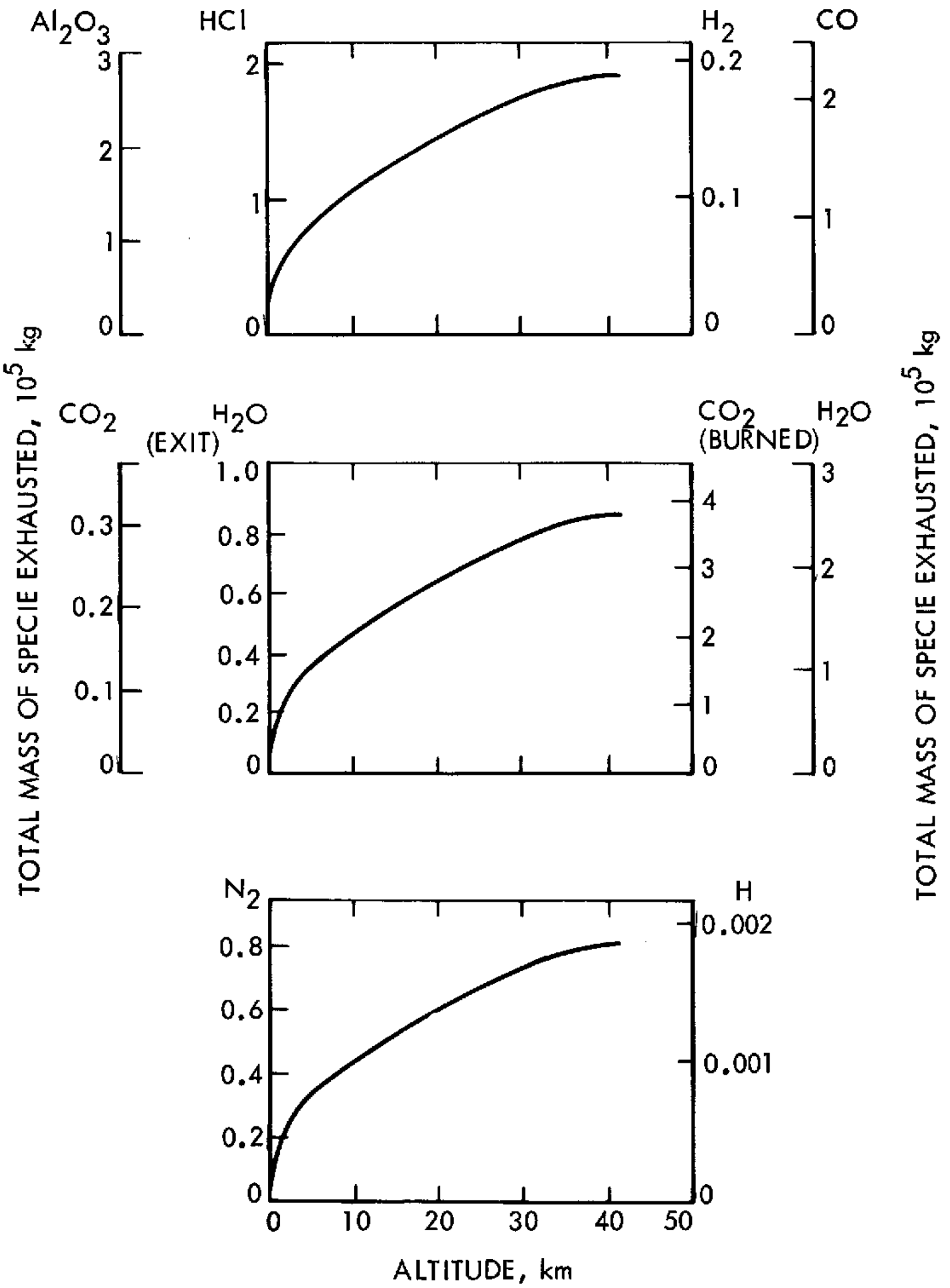

Fig. 5b. Total production of indicated species to given altitude: Mission 2

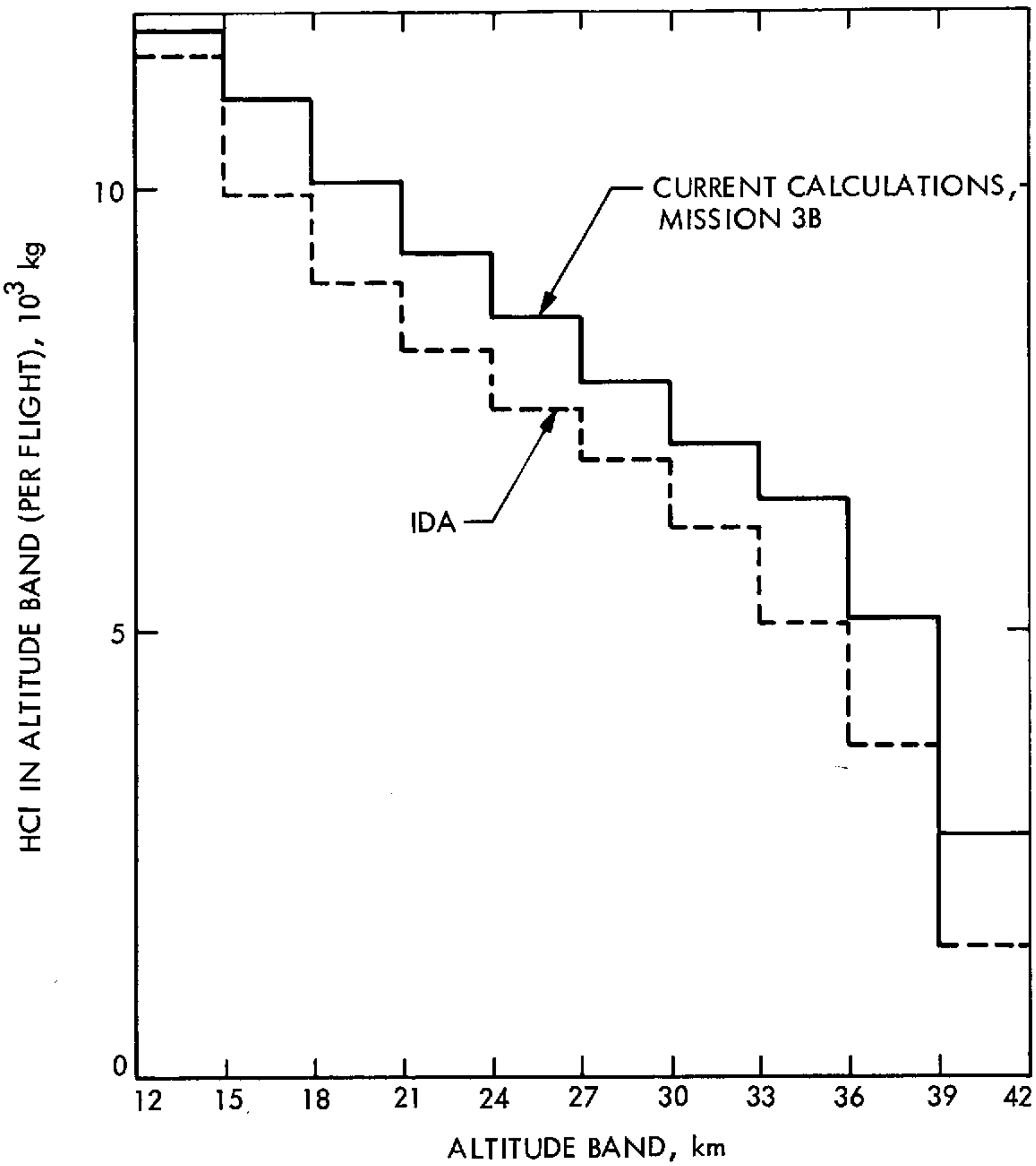

Fig. 6. Comparison of current calculations with IDA results

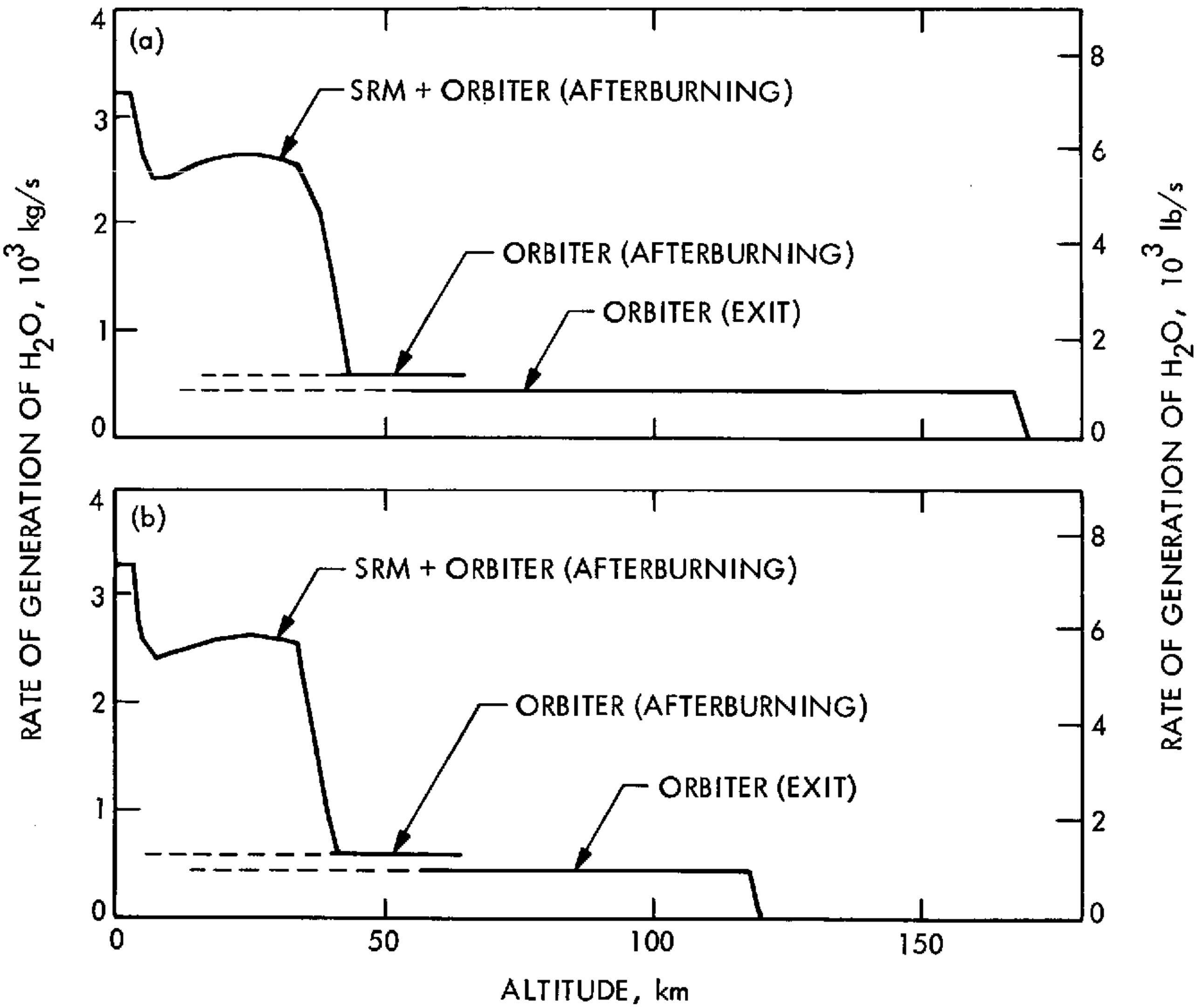

Fig. 7. Rate of generation of H_2O versus altitude: (a) Mission 3B, (b) Mission 2

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