Theoretical Notes
Note 245

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NON-EQUILIBRIUM CONDUCTIVITY OF AIR INDUCED BY IONIZING RADIATION

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ABSTRACT

This report summarizes computer results for the time-dependent non-equilibrium conductivity of air subjected to an intense dose of ionizing radiation in the presence of a strong electric field. A two-temperature model is employed throughout, and an appropriate set of reaction equations for the time-dependent specie concentrations are solved.

Results are presented for the conductivity, the electron concentration, and the electron and gas temperatures for several cases of interest.

1.0 INTRODUCTION

When air is subjected to a short, very intense pulse of ionizing radiation the various degrees of freedom of the air respond at significantly different rates. The ionizing radiation is absorbed in electronic degrees of excitation -- exciting, dissociating, and ionizing the ambient air molecules. The kinetic temperature of the heavy particles remains ambient and the free electrons quickly thermalize to a temperature of the order of electron volts ($\sim 10^4$°K). Only after times of the order of nanoseconds (10^{-9} seconds) do the electron and heavy particle temperatures equilibrate, and the air then relaxes to near equilibrium conditions with a time "constant" of the order of microseconds -- depending on the final air temperature obtained. The late time residual effect of the ionizing source resides mainly in the abnormally large concentrations of ozone O_3, NO, and NO_2 -- depending again on the final temperature and, hence, total dose. In the presence of a strong electric field, the electron temperature and concentration remain far from equilibrium for as long as the field is applied -- significantly changing the air conductivity and increasing the absorption of the electric field energy.

These non-equilibrium effects have long been of interest to EMP studies (Ref. 1), and have recently been applied to free-free radiation emission studies (Ref. 2). Earlier studies were restricted to doses and field strengths such that the final air temperature and chemistry was essentially ambient. We are interested here in cases for which this is not true, and the

time evolution of the chemical composition and energy components of the non-equilibrium air must be followed in detail.

The general chemistry code ALCHEM has been suitably modified and applied to this purpose. It is described in Section 2.0 below, and our results are presented in Section 3.0.

2.0 THE CHEMISTRY CODE ALCHEM

The code ALCHEM is a generalization of the code developed by Scheibe of Mission Research (Ref. 3) and Gunton of Lockheed (Ref. 4) for high altitude deionization studies. The code has been extensively modified into a multi-temperature model with attention to the detailed energetics. The specific elements of our calculations are discussed in turn.

2.1.1 Included Species.

The species included in our calculations are listed in Table I. Water molecules have not been included although their important effect on the detailed final stages of electron thermalization is well known (Ref. 1). Similarly, the hydrated molecular ions responsible for the late time D-Region deionization are omitted; their inclusion was found to not change our results during the time intervals of interest.

The various entries in Table I are:

(a) The "zero point" or dissociation energy of each species (eV/particle)

(b) Six specie identifiers:

(i) Specie type:

0 - electrons

1 - neutral specie

2 - positive ion

3 - negative ion

4 - total neutral concentration

5 - total positive concentration

6 - total negative concentration

(ii) Number of Nitrogen atoms per molecule

(iii) Number of Oxygen atoms per molecule

(iv) Number of Carbon atoms per molecule

(v) Number of Hydrogen atoms per molecule

(vi) (not used)

(c) f, Number of classical degrees of freedom for the specie

(d) If not equal to zero, the specific heat tabulations of Gilmore are used (from Ref. 5)
If equal to zero, the specific heat per molecule is taken to be

$$C_v = f/2 - 1 + \frac{\omega_0}{kT}\left(e^{\omega_0/kT} - 1\right)^{-1}$$

(e) ω_0, the vibrational spacing (eV)

TABLE I.

SPECIES SPECIFICATION CARDS

		(a)	(b)	(c)	(d)	(e)
1	E	0.00	0-0-0-0-0-0	3	-0	-0.0000
2	N2	0.00	1 2-0-0-0-0	7	1	.2890
3	O2	0.00	1-0 2-0-0-0	7	0	.1930
4	O2(1D)	.98	1-0 2-0-0-0	7	-0	.1839
5	N	4.88	1 1-0-0-0-0	3	0	-0.0000
6	N(2D)	7.26	1 1-0-0-0-0	3	-0	-0.0000
7	O	2.56	1-0 1-0-0-0	3	9	-0.0000
8	NO	.93	1 1 1-0-0-0	7	3	.2326
9	O3	1.51	1-0 3-0-0-0	12	-0	.1000
10	NO2	.37	1 1 2-0-0-0	12	-0	.1530
11	N2O	.88	1 2 1-0-0-0	12	-0	.1690
12	CO2	-4.08	1-0 2 1-0-0	12	-0	.1820
13	TE	-0.00	1-0-0-0-0-0	-0	-0	-0.0000
14	N+	19.41	2 1-0-0-0-0	3	8	-0.0000
15	O+	16.18	2-0 1-0-0-0	3	10	-0.0000
16	N2+	15.58	2 2-0-0-0-0	7	2	.2696
17	O2+	12.06	2-0 2-0-0-0	7	6	.2322
18	NO+	10.20	2 1 1-0-0-0	7	4	.2907
19	N3+	19.00	2 3-0-0-0-0	12	-0	-0.0000
20	N4+	15.00	2 4-0-0-0-0	18	-0	-0.0000
21	O4+	11.65	2-0 4-0-0-0	18	-0	-0.0000
22	CO3-	-5.50	3-0 3 1-0-0	18	-0	-0.0000
23	CO4-	-4.80	3-0 4 1-0-0	24	-0	-0.0000
24	O-	-1.08	3-0 1-0-0-0	3	-0	-0.0000
25	O2-	-.43	3-0 2-0-0-0	7	-0	.1320
26	O3-	-.60	3-0 3-0-0-0	12	-0	.1320
27	M	-0.00	4-0-0-0-0-0	-0	-0	-0.0000
28	M+	-0.00	5-0-0-0-0-0	-0	-0	-0.0000
29	M-	-0.00	6-0-0-0-0-0	-0	-0	-0.0000

SPECIE INDICES- NEUTRAL(2-13) POSITIVE(14-21) NEGATIVE(22-26) TOTALS- 27 28 29

2.1.2 Source and Initial Conditions.

Three ionization sources are employed in the code at present:

1. Instantaneous energy deposition at time t = 0

$$q(t) = Q_0\ \delta(t)\ eV/cm^3 sec.$$

2. The continuous source

$$q(t) = \frac{Q_0}{\tau_1}\left(1 + \frac{\tau_2}{\tau_1}\right) e^{-t/\tau_1}\left(1 - e^{-t/\tau_2}\right) \frac{eV}{cm^3 sec}$$

where

$$\tau_2 << \tau_1, \text{ and } \int_0^\infty q(t)dt = Q_0 \left(\frac{eV}{cm^3}\right)$$

3. The source

$$q(t) = q_0(t/\tau_1),\ (t \leqslant \tau_1)$$
$$= q_0,\ (\tau_1 \leqslant t \leqslant \tau_2)$$
$$= 0,\ \ (t > \tau_2).$$

Most of the results we report here are for the third source above, with $\tau_1 = 2x10^{-9}$sec, $\tau_2 = 10^{-8}$sec, and we assume a constant electric field ξ(v/cm) only during the time $t \leq \tau_1$.

For initial conditions, we follow Gilmore (Ref. 6) -- reproduced here as particles per ion pair --

	Particles per ion pair	Energy Spent per ion pair (eV)
N_2^+	0.62	9.66 eV
O_2^+	0.16	1.93
N^+	0.18	3.49
O^+	0.04	0.65

	Particles per ion pair	Energy Spent per ion pair (eV)
$O_2(^1\Delta)$	0.4	0.49
N	0.45	2.20
$N(^2D)$	0.61	4.43
O	1.3	3.33
		26.18eV

Observing that 33.73eV are deposited per ion pair produced, that 26.18eV are accounted for by dissociation and ionization, and assuming the kinetic energies of the heavy particles unchanged, we obtain 7.55eV kinetic energy per electron produced, corresponding to an electron temperature of 58,400°K.

2.1.3 The Reaction Set.

The reaction set we employ is adapted from Scheibe's D-Region set (Ref. 3), extended to include some fast electron reactions from NRL (Ref. 7) and from EGG (Ref. 2). Except for the fast electron reactions, our rates were generally taken from the DNA Reaction Rate Handbook (Ref. 8).

The various reactions we have considered are listed in Table II, including their rates, R, at ambient temperature, the rate coefficients A,B,C, the reaction type N, and the energy emitted per reaction, ΔE(eV). The various reaction rate prescriptions employed are identified by the reaction type index N, defined as follows:

N = 0: Electron production reaction due to the

ionizing radiation source q(t). The reaction rate is

$R = A\left(\frac{q(t)}{33.73}\right)$ reaction/sec per target particle.

N = 1: Photo dissociation. R = A

N = 2: O_2 photo dissociation. $R = 6.33\times10^{-3}Ae^{-h/17.7\ell}$ where h = altitude (km).

N = 3: O_3 photo dissociation. (Altitude dependent).

N = 4: The composite reaction

$O^- + N_2O \rightarrow NO^- + NO$, $(R_1 = 2.3\times10^{-10})$

and

$NO^- + O_2 \rightarrow NO + O_2^-$, $(R_2 = 5\times10^{-10})$

resulting in

$O^- + N_2O + O_2 \rightarrow O_2^- + 2NO$, with reaction rate $R = 2\times10^{-10}\left(\frac{300}{T}\right)^B e^{-C/T}$

N = 5: The NRL reaction "KTV" (Ref. 7)

$O^+ + N_2 \rightarrow NO^+ + N$

$R = 10^{-12}(1 - x)\{1.2(1+x) + 50x^2 + 120x^3 + 260x^4+400x^5+500x^6(1+x+x^2)\}$

where $x = \exp(-3481/T_\nu)$, where T_ν is the N_2 vibrational temperature (^oK), here taken to be the electron temperature T_e.

N = 6: Dissociative capture on O_2:

$O_2 + e \rightarrow O^- + O$, the reaction rate being a fit to the thermal average of the cross section quoted by Kroll and Watson (Ref. 9),

$$R = \frac{1.66\times10^{-10}}{\theta^n} e^{-3.7/\theta}(1 - e^{-.264\theta^2})$$

$\theta = kT_e$ is the electron "temperature" in eV, and $n = 1$ for $\theta \geq 1.0$eV

$n = 0$ for $\theta < 1.0$eV

N = 7: $R = A$

N = 8: $R = A(300/T)^B$

N = 9: $R = A(300/T)^B e^{-C/T}$

} T being the gas temperature (^oK)

N = 10: Radiative Decay.

$R = A$, the Einstein A-value, and the photon energy $\omega = C$

N = 11-14: Not used.

N = 15: Dissociative recombination - vibrations at gas temperature T_A

$$R = A\left(\frac{300}{T_e}\right)^B e^{-C/T_e}(1 - e^{-D/T_A})$$

N = 16: Dissociative recombination - vibrations at the electron temperature $T_e(^oK)$

$$R = A\left(\frac{300}{T_e}\right)^B e^{-C/T_e}(1 - e^{-D/T_e})$$

N = 17: $R = A$

N = 18: $R = A(300/T_e)^B$

N = 19: $R = A(300/T_e)^B e^{-C/T_e}$

N = 800 + n: The n^{th} electronic/ionization rate tabulated by Ali (Ref. 7 - reproduced as Table III.)

N = 900 + n: The inverse of the excitation rates of Ali/NRL:

$R(900+n) = Ae^{-C/T_e}R(800+n)$

TABLE II

	REACTIONS								RATES	COEFFICIENTS				
									R	A	B	C	N	ΔE(eV)
1	N2	+			=	N2+	+	E	0.	6.20E-01	-0.00	-0.00	0	-1.558E+01
2	N2	+			=	N(2D)	+	N+ + E	0.	1.60E-01	-0.00	-0.00	0	-2.667E+01
3	N2	+			=	N(2D)	+	N	0.	4.50E-01	-0.00	-0.00	0	-1.214E+01
4	O2	+			=	O2+	+	E	0.	1.60E-01	-0.00	-0.00	0	-1.206E+01
5	O2	+			=	O2(1D)+			0.	4.00E-01	-0.00	-0.00	0	-9.770E-01
6	O2	+			=	O	+	O	0.	6.50E-01	-0.00	-0.00	0	-5.120E+00
7	O	+			=	O+	+	E	0.	4.00E-02	-0.00	-0.00	0	-1.362E+01
8	N	+			=	N+	+	E	0.	2.00E-02	-0.00	-0.00	0	-1.453E+01
9	O	+	O2	+ M	=	O3	+	+ M	6.12E-34	5.50E-34	2.60	0.00	8	1.050E+00
10	O	+	N2		=	NO	+	N	7.05E-68	1.00E-10	-0.00	37900.00	9	-3.250E+00
11	O	+	NO	+ M	=	NO2	+	+ M	1.11E-31	1.00E-31	2.50	0.00	8	3.120E+00
12	O	+	NO		=	O2	+	N	1.83E-42	5.30E-12	-0.00	20200.00	9	-1.390E+00
13	O	+	NO2		=	NO	+	O2	5.65E-12	1.60E-11	0.00	300.00	9	2.000E+00
14	O	+	O	+ O2	=	O2	+	+ O2	5.62E-33	5.46E-33	.72	0.00	8	5.120E+00
15	O	+	O	+ N2	=	O2	+	+ N2	2.98E-33	2.87E-33	.95	0.00	8	5.120E+00
16	O	+	NO		=	NO2	+		6.73E-17	6.20E-17	2.00	0.00	8	3.120E+00
17	O	+	O3		=	O2(1D)+	O2		4.77E-15	7.00E-12	0.00	2100.00	9	3.093E+00
18	O	+	O3		=	O2	+	O2	4.77E-15	7.00E-12	0.00	2100.00	9	4.070E+00
19	N	+	O2		=	NO	+	O	2.23E-17	2.40E-11	0.00	4000.00	9	1.390E+00
20	N	+	NO		=	N2	+	O	2.20E-11	2.20E-11	0.00	0.00	7	3.250E+00
21	N	+	NO2		=	NO	+	NO	9.00E-12	9.00E-12	0.00	0.00	7	3.390E+00
22	N	+	NO2		=	N2O	+	O	9.00E-12	9.00E-12	0.00	0.00	7	1.810E+00
23	N	+	O3		=	NO	+	O2	5.16E-13	3.40E-11	-.50	1200.00	9	5.460E+00
24	N	+	NO	+ M	=	N2O	+	+ M	3.10E-36	1.00E-34	0.00	1000.00	9	4.930E+00
25	N	+	N	+ N2	=	N2	+	+ N2	8.85E-33	8.54E-33	.87	0.00	8	9.760E+00
26	N	+	N	+ O2	=	N2	+	+ O2	5.17E-33	5.00E-33	.83	0.00	8	9.760E+00
27	N	+	O	+ N2	=	NO	+	+ N2	1.09E-32	1.07E-32	.50	0.00	8	6.510E+00
28	N	+	O	+ O2	=	NO	+	+ O2	1.11E-32	1.07E-32	.95	0.00	8	6.510E+00
29	N	+	N		=	N2	+		1.00E-17	1.00E-17	0.00	0.00	7	9.760E+00
30	N	+	O		=	NO	+		2.00E-17	2.00E-17	0.00	0.00	7	6.510E+00
31	N(2D)	+	O2		=	NO	+	O	6.00E-12	6.00E-12	0.00	0.00	7	3.770E+00
32	N(2D)	+	N2		=	N	+	N2	1.60E-14	1.60E-14	-0.00	-0.00	7	2.380E+00
33	N(2D)	+	NO		=	N2	+	O	7.00E-11	7.00E-11	0.00	0.00	7	5.630E+00
34	N(2D)	+	NO		=	NO	+	N	7.00E-11	7.00E-11	-0.00	-0.00	7	2.380E+00
35	O2	+	E		=	O	+	O-	2.06E-76	-0.	-0.00	-0.00	6	-1.480E+00
36	O2(1D)+	O3			=	O2	+	O2 + O	2.70E-15	4.50E-11	0.00	2800.00	9	-7.300E-02
37	O2(1D)+	N			=	O2	+	N	3.00E-15	3.00E-15	0.00	0.00	7	9.770E-01
38	O2(1D)+	O			=	O2	+	O	1.00E-16	1.00E-16	0.00	0.00	7	9.770E-01
39	O2(1D)+	N2			=	O2	+	N2	1.00E-20	1.00E-20	0.00	0.00	7	9.770E-01
40	O2(1D)+	O2			=	O2	+	O2	2.40E-18	2.40E-18	0.00	0.00	7	9.770E-01
41	O2(1D)+				=	O2	+		2.60E-04	2.60E-04	0.00	0.00	7	9.770E-01
42	NO	+	O3		=	NO2	+	O2	1.04E-14	9.50E-13	0.00	1300.00	9	2.070E+00
43	N2+	+	E		=	N(2D)	+	N	1.70E-07	1.70E-07	.39	0.00	16	3.440E+00
44	N2+	+	E		=	N(2D)	+	N(2D)	1.40E-08	1.40E-08	.39	0.00	16	1.060E+00
45	NO+	+	E		=	N	+	O	1.00E-07	1.00E-07	1.00	0.00	15	2.760E+00
46	NO+	+	E		=	N(2D)	+	O	3.00E-07	3.00E-07	1.00	0.00	15	3.800E-01
47	N2+	+	NO		=	NO+	+	N2	3.30E-10	3.30E-10	0.00	0.00	7	6.310E+00
48	N2+	+	O2		=	O2+	+	N2	5.10E-11	5.00E-11	.50	0.00	8	3.520E+00
49	N2+	+	N2	+ M	=	N4+	+	M	5.21E-29	5.00E-29	1.00	-0.00	8	5.800E-01
50	N2+	+	O		=	O+	+	N2	6.00E-12	6.00E-12	0.00	0.00	7	1.960E+00
51	N2+	+	N		=	N+	+	N2	1.00E-11	1.00E-11	0.00	0.00	7	1.050E+00
52	N+	+	NO		=	N	+	NO+	8.00E-10	8.00E-10	0.00	0.00	7	5.260E+00
53	N+	+	O2		=	N	+	O2+	3.00E-10	3.00E-10	0.00	0.00	7	2.470E+00
54	N+	+	O		=	N	+	O+	1.00E-12	1.00E-12	0.00	0.00	7	9.100E-01
55	O+	+	NO		=	NO+	+	O	1.30E-12	1.30E-12	0.00	0.00	7	4.350E+00
56	O+	+	O2		=	O2+	+	O	2.04E-11	2.00E-11	.50	0.00	8	1.560E+00
57	O2+	+	NO		=	NO+	+	O2	6.30E-10	6.30E-10	0.00	0.00	7	2.790E+00
58	O2+	+	N2		=	NO+	+	NO	1.00E-16	1.00E-16	0.00	0.00	7	9.300E-01
59	N+	+	O2		=	O	+	NO+	3.00E-10	3.00E-10	0.00	0.00	7	6.650E+00
60	N+	+	O2		=	NO	+	O+	1.00E-12	1.00E-12	0.00	0.00	7	2.300E+00

61	O+	+ NO		= O2+	+ N		1.00E-13	1.00E-13	0.00	0.00	7	1.700E-01
62	O+	+ N2		= NO+	+ N		1.20E-12	1.20E-12	.50	0.00	5	1.100E+00
63	O+	+ N2O		= NO+	+ NO		1.30E-09	1.30E-09	0.00	0.00	7	5.930E+00
64	N2+	+ O		= NO+	+ N(2D)		7.00E-11	7.00E-11	0.00	0.00	7	6.800E-01
65	N2+	+ O		= NO+	+ N		7.00E-11	7.00E-11	0.00	0.00	7	3.060E+00
66	O2+	+ NO2		= NO+	+ O3		1.00E-11	1.00E-11	0.00	0.00	7	7.200E-01
67	O2+	+ N		= NO+	+ O		1.80E-10	1.80E-10	0.00	0.00	7	4.180E+00
68	O2+	+ N		= O+	+ NO		1.50E-14	1.10E-11	0.00	1900.00	9	-1.700E-01
69	N4+	+ E		= N2	+ N2		2.19E-06	2.10E-06	1.00	-0.00	8	1.500E+01
70	N4+	+ O2		= N2	+ N2	+ O2+	4.00E-10	4.00E-10	-0.00	-0.00	7	2.940E+00
71	O2+	+ O2	+ M	= O4+	+	+ M	3.12E-30	3.00E-30	1.00	0.00	8	4.100E-01
72	O4+	+	+ M	= O2+	+ O2	+ M	1.50E-14	5.00E-07	1.00	5000.00	9	-4.100E-01
73	O4+	+ O		= O2+	+ O3		3.00E-10	3.00E-10	0.00	0.00	7	6.400E-01
74	O4+	+ NO		= NO+	+ O2	+ O2	5.00E-10	5.00E-10	0.00	0.00	7	2.380E+00
75	O4+	+ E		= O2	+ O2		1.56E-06	1.50E-06	1.00	0.00	8	1.165E+01
76	O2	+ E	+ O2	= O2-	+	+ O2	1.82E-30	1.40E-29	1.00	600.00	9	4.300E-01
77	O2-	+	+ O2	= O2	+ E	+ O2	9.84E-19	2.70E-10	-.50	5590.00	9	-4.300E-01
78	O2	+ E	+ N2	= O2-	+	+ N2	1.00E-31	1.00E-31	0.00	0.00	7	4.300E-01
79	O2-	+	+ N2	= O2	+ E	+ N2	5.16E-20	1.90E-12	-1.50	5000.00	9	-4.300E-01
80	O3	+ E		= O-	+ O2		8.47E-12	9.00E-12	-1.50	0.00	8	2.590E+00
81	O	+ E		= O-	+		1.30E-15	1.30E-15	0.00	0.00	7	3.640E+00
82	O2-	+ O		= O3	+ E		3.00E-10	3.00E-10	0.00	0.00	7	6.200E-01
83	O2-	+ N		= NO2	+ E		5.00E-10	5.00E-10	0.00	0.00	7	4.080E+00
84	O-	+ NO		= NO2	+ E		2.00E-10	2.00E-10	0.00	0.00	7	-5.200E-01
85	O-	+ N		= NO	+ E		2.20E-10	2.20E-10	0.00	0.00	7	2.870E+00
86	O-	+ O		= O2	+ E		2.00E-10	2.00E-10	0.00	0.00	7	1.480E+00
87	O2(1D)+	O2-		= O2	+ O2	+ E	2.00E-10	2.00E-10	0.00	0.00	7	5.470E-01
88	O2(1D)+	O-		= O3	+ E		3.00E-10	3.00E-10	0.00	0.00	7	-1.613E+00
89	O2-	+ O		= O-	+ O2		1.00E-11	1.00E-11	0.00	0.00	7	3.210E+00
90	O2-	+ O3		= O3-	+ O2		4.00E-10	4.00E-10	0.00	0.00	7	1.680E+00
91	O-	+ O3		= O3-	+ O		5.30E-10	5.30E-10	0.00	0.00	7	-1.530E+00
92	CO3-	+ O		= O2-	+ CO2		8.00E-11	8.00E-11	0.00	0.00	7	1.570E+00
93	O3-	+ CO2		= CO3-	+ O2		4.00E-10	4.00E-10	0.00	0.00	7	8.200E-01
94	O3-	+ O		= O2-	+ O2		1.00E-11	1.00E-11	0.00	0.00	7	2.390E+00
95	O-	+ O2	+ M	= O3-	+	+ M	1.04E-30	1.00E-30	1.00	0.00	8	-4.800E-01
96	CO4-	+ O		= O3-	+ CO2		7.50E-11	7.50E-11	0.00	0.00	7	2.440E+00
97	O2-	+ CO2	+ M	= CO4-	+	+ M	2.08E-29	2.00E-29	1.00	0.00	8	2.900E-01
98	CO4-	+ O		= CO3-	+ O2		1.50E-10	1.50E-10	0.00	0.00	7	3.260E+00
99	CO4-	+	+ M	= O2-	+ CO2	+ M	4.84E-18	3.30E-02	0.00	10500.00	9	-2.900E-01
100	NO+	+ O-		= NO	+ O		2.04E-07	2.00E-07	.50	0.00	8	5.630E+00
101	NO+	+ O2-		= NO	+ O2		2.04E-07	2.00E-07	.50	0.00	8	8.840E+00
102	NO+	+ O3-		= NO	+ O3		2.04E-07	2.00E-07	.50	0.00	8	7.160E+00
103	NO+	+ CO3-		= NO	+ CO2	+ O	2.04E-07	2.00E-07	.50	0.00	8	5.290E+00
104	NO+	+ CO4-		= NO	+ CO2	+ O2	2.04E-07	2.00E-07	.50	0.00	8	8.550E+00
105	O2+	+ O-		= O2	+ O		2.04E-07	2.00E-07	.50	0.00	8	8.420E+00
106	O2+	+ O2-		= O2	+ O2		4.08E-07	4.00E-07	.50	0.00	8	1.163E+01
107	O2+	+ O3-		= O2	+ O3		2.04E-07	2.00E-07	.50	0.00	8	9.950E+00
108	O2+	+ CO3-		= O2	+ CO2	+ O	2.04E-07	2.00E-07	.50	0.00	8	8.080E+00
109	O2+	+ CO4-		= O2	+ CO2	+ O2	2.04E-07	2.00E-07	.50	0.00	8	1.139E+01
110	O4+	+ O-		= O2	+ O	+ O2	1.02E-07	1.00E-07	.50	0.00	8	8.010E+00
111	O4+	+ O2-		= O2	+ O2	+ O2	1.02E-07	1.00E-07	.50	0.00	8	1.122E+01
112	O4+	+ O3-		= O2	+ O3	+ O2	1.02E-07	1.00E-07	.50	0.00	8	9.540E+00
113	O4+	+ CO3-		= O2	+ CO2	+ O3	1.02E-07	1.00E-07	.50	0.00	8	8.720E+00
114	O4+	+ CO4-		= O2	+ CO2	+ O2	1.02E-07	1.00E-07	.50	0.00	8	1.093E+01
115	N2+	+ E	+ M	= N2	+	+ M	1.11E-26	1.00E-26	2.50	-0.00	8	1.558E+01
116	N2+	+ O2-		= N2	+ O2		1.60E-07	1.60E-07	-0.00	-0.00	7	1.515E+01
117	N2+	+ O2-	+ M	= N2	+ O2	+ M	3.00E-25	3.00E-25	-0.00	-0.00	7	1.515E+01
118	O2+	+ N2		= O2	+ N2+		1.00E-10	1.00E-10	-0.00	-0.00	7	-3.520E+00
119	O+	+ N2		= O	+ N2+	+ M	2.00E-11	2.00E-11	-0.00	-0.00	7	-1.960E+00
120	O2+	+ E	+ M	= O2	+	+ M	1.11E-26	1.00E-26	2.50	-0.00	8	1.206E+01
121	O2+	+ E		= O	+ O		2.16E-07	2.10E-07	.70	-0.00	8	6.940E+00
122	O2+	+ O2-	+ M	= O2	+ O2	+ M	3.00E-25	3.00E-25	-0.00	-0.00	7	1.163E+01

123	N+	+ E	+ M	= N	+	+ M	1.11E-26	1.00E-26	2.50	-0.00	8	1.453E+01
124	N+	+ O2-		= N	+ O2		5.00E-08	5.00E-08	-0.00	-0.00	7	1.410E+01
125	N+	+ O2-		= NO	+ O		5.00E-08	5.00E-08	-0.00	-0.00	7	1.549E+01
126	O+	+ E	+ M	= O	+	+ M	1.11E-26	1.00E-26	2.50	-0.00	8	1.362E+01
127	O+	+ N2	+ M	= NO+	+ N	+ M	2.00E-28	2.00E-28	-0.00	-0.00	7	1.100E+00
128	O+	+ O2-		= O	+ O2		1.00E-07	1.00E-07	-0.00	-0.00	7	1.319E+01
129	O+	+ O2-	+ M	= O	+ O2	+ M	3.00E-25	3.00E-25	-0.00	-0.00	7	1.319E+01
130	N4+	+ O2-		= N2	+ N2	+ O2	1.00E-07	1.00E-07	-0.00	-0.00	7	1.457E+01
131	NO+	+ E	+ M	= NO	+	+ M	1.11E-26	1.00E-26	2.50	-0.00	8	9.270E+00
132	N3+	+ E		= N	+ N2		7.29E-07	7.00E-07	1.00	-0.00	8	1.412E+01
133	N3+	+ E	+ E	= N2	+ E		1.20E-19	1.00E-19	4.50	-0.00	8	1.900E+01
134	N3+	+ O2		= NO+	+ O	+ N2	3.30E-11	3.30E-11	-0.00	-0.00	7	6.240E+00
135	N3+	+ O2		= O2+	+ N	+ N2	3.30E-11	3.30E-11	-0.00	-0.00	7	2.060E+00
136	N+	+ N2	+ M	= N3+	+	+ M	2.00E-29	2.00E-29	-0.00	-0.00	7	4.100E-01
137	O+	+ E	+ E	= O	+ E		1.00E-19	-0.	-0.00	-0.00	955	1.362E+01
138	N+	+ E	+ E	= N	+ E		1.00E-50	-0.	-0.00	-0.00	960	1.453E+01
139	NO+	+ E	+ E	= NO	+ E		1.00E-19	-0.	-0.00	-0.00	965	9.270E+00
140	N2+	+ E	+ E	= N2	+ E		1.00E-19	-0.	-0.00	-0.00	966	1.558E+01
141	O2+	+ E	+ E	= O2	+ E		1.00E-19	-0.	-0.00	-0.00	970	1.206E+01
142	O	+ E		= O+	+ E	+ E	1.59E-89	-0.	-0.00	-0.00	805	-1.362E+01
143	N	+ E		= N(2D)	+ E		4.32E-23	-0.	-0.00	-0.00	806	-2.380E+00
144	N(2D)	+ E		= N	+ E		1.37E-63	4.00E-01	-0.00	27700.00	906	2.380E+00
145	N	+ E		= N+	+ E	+ E	1.00E-50	-0.	-0.00	-0.00	810	-1.453E+01
146	NO	+ E		= NO+	+ E	+ E	5.80E-64	-0.	-0.00	-0.00	815	-9.270E+00
147	N2	+ E		= N2+	+ E	+ E	2.46-103	-0.	-0.00	-0.00	816	-1.558E+01
148	O2	+ E		= O2(1D)+	E		1.80E-15	-0.	-0.00	-0.00	818	-9.770E-01
149	O2(1D)+	E		= O2	+ E		1.18E-31	1.50E+00	-0.00	11300.00	918	9.770E-01
150	O2	+ E		= O2+	+ E	+ E	6.19E-18	-0.	-0.00	-0.00	820	-1.206E+01
151	TE	+		= TE	+		8.83E+09	-0.	-0.00	-0.00	20	0.

N = 950 + n: The inverse of the ionization rates of Ali/NRL - Reaction rate obtained from the direct reactions of Table III with Saha relations at temperature T_e, using partition functions from Reference 5, Table B-VI.

In the presence of the strong electric fields of interest here, the Druyvesteyn distribution is a more appropriate electron energy distribution than the thermal average we have employed here (Ref. 11). Except for the strongest fields we have considered, this modification results in only few percent corrections to the conductivity. The stronger high energy tail of the Druyvesteyn distribution somewhat enhances ionization processes and slightly increases the electron concentration.

The electron swarm energy equation is assigned Reaction type 20. Expressed in terms of the electron temperature, T_e, it is written

$$\frac{dT_e}{dt} = \overset{(1)}{-\left(\frac{T_e - T_A}{\tau}\right)} \overset{(2)}{- \frac{T_e}{n_e}\frac{d\tilde{n}_e}{dt}} \overset{(3)}{- \frac{1}{\left(\frac{3}{2}n_e k\right)}\frac{dE_B}{dt}} + \overset{(4)}{\left(\frac{dT_e}{dt}\right)_{\xi\text{-field}}} + \overset{(5)}{\left(\frac{dT_e}{dt}\right)_{\text{source}}}$$

The five contributions we consider are:

1. The electron energy loss due to collision with the cooler gas particles at temperature T_A. The energy exchange time τ is evaluated as a function of time using the calculated specie concentrations and the relaxation times per specie particle of Table IV (from Ref. 5).

TABLE III

Electron impact excitation and ionization rates (sec^{-1} per molecule). The temperatures are in eV and the reactions are numbered as follows:

1. O: $(^3P \rightarrow ^1D)$
2. O: $(^3P \rightarrow ^1S)$
3. O: $(^1D \rightarrow ^1S)$
4. O: $2p^4(^3P) \rightarrow 2p^3 3s(^3S)$
5. O: Ionization
6. N: $(^4S \rightarrow ^2D)$
7. N: $(^4S \rightarrow ^2P)$
8. N: $(^2D \rightarrow ^2P)$
9. N: $2p^3(^4S) \rightarrow 2p^2 3s(^4P)$
10. N: Ionization
11. N_2: $(X^1\Sigma \rightarrow A^3\Sigma)$
12. N_2: $(X^1\Sigma \rightarrow B^3\pi)$
13. N_2: $(X^1\Sigma \rightarrow C^3\pi)$
14. N_2: $(X^1\Sigma \rightarrow D^3\Sigma)$
15. NO: Ionization
16. N_2: Ionization
17. N_2^+: $(X^2\Sigma \rightarrow B^2\Sigma)$
18. O_2: $(X^2\pi \rightarrow a^1\Delta)$
19. O_2: $(X^2\pi \rightarrow b^1\Sigma)$
20. O_2: Ionization

The data are from the compilation of Ali (Ref. 7), except for the NO ionization rate, for which the experimental data of Rapp and Englander-Golden were employed (Ref. 10).

TABLE III, Cont'd

ALI/NRL EXCITATION/IONIZATION RATES (1/SEC)

TEMP	1	2	3	4	5
.1	1.73E-18	1.78E-29	1.53E-19	6.19E-49	1.10E-67
.2	5.58E-14	1.96E-19	1.44E-14	8.17E-29	3.14E-38
.3	2.01E-12	2.10E-16	6.99E-13	4.60E-22	2.08E-28
.4	1.28E-11	7.13E-15	4.95E-12	1.15E-18	1.71E-23
.5	4.00E-11	6.04E-14	1.61E-11	1.30E-16	1.55E-20
.6	8.66E-11	2.55E-13	3.53E-11	3.11E-15	1.46E-18
.7	1.52E-10	7.25E-13	6.17E-11	3.05E-14	3.81E-17
.8	2.32E-10	1.60E-12	9.40E-11	1.71E-13	4.43E-16
.9	3.24E-10	2.98E-12	1.30E-10	6.59E-13	3.01E-15
1.0	4.24E-10	4.93E-12	1.69E-10	1.95E-12	1.40E-14
1.1	5.30E-10	7.48E-12	2.09E-10	4.77E-12	4.95E-14
1.2	6.38E-10	1.06E-11	2.49E-10	1.01E-11	1.42E-13
1.3	7.47E-10	1.43E-11	2.90E-10	1.90E-11	3.50E-13
1.4	8.56E-10	1.85E-11	3.29E-10	3.28E-11	7.58E-13
1.5	9.63E-10	2.32E-11	3.66E-10	5.26E-11	1.49E-12
1.6	1.07E-09	2.82E-11	4.05E-10	7.96E-11	2.69E-12
1.7	1.17E-09	3.37E-11	4.41E-10	1.15E-10	4.54E-12
1.8	1.27E-09	3.94E-11	4.76E-10	1.59E-10	7.26E-12
1.9	1.36E-09	4.53E-11	5.09E-10	2.13E-10	1.11E-11
2.0	1.46E-09	5.15E-11	5.41E-10	2.76E-10	1.62E-11
2.1	1.54E-09	5.78E-11	5.72E-10	3.50E-10	2.29E-11
2.2	1.63E-09	6.42E-11	6.01E-10	4.34E-10	3.14E-11
2.3	1.71E-09	7.07E-11	6.30E-10	5.28E-10	4.20E-11
2.4	1.79E-09	7.72E-11	6.57E-10	6.31E-10	5.49E-11
2.5	1.87E-09	8.37E-11	6.82E-10	7.44E-10	7.05E-11
2.6	1.94E-09	9.02E-11	7.07E-10	8.65E-10	8.84E-11
2.7	2.01E-09	9.67E-11	7.31E-10	9.94E-10	1.09E-10
2.8	2.07E-09	1.03E-10	7.53E-10	1.13E-09	1.34E-10
2.9	2.13E-09	1.10E-10	7.75E-10	1.27E-09	1.61E-10
3.0	2.20E-09	1.16E-10	7.96E-10	1.42E-09	1.92E-10
3.1	2.25E-09	1.22E-10	8.16E-10	1.58E-09	2.26E-10
3.2	2.31E-09	1.28E-10	8.35E-10	1.74E-09	2.64E-10
3.3	2.36E-09	1.34E-10	8.53E-10	1.90E-09	3.05E-10
3.4	2.41E-09	1.40E-10	8.71E-10	2.07E-09	3.51E-10
3.5	2.46E-09	1.45E-10	8.88E-10	2.24E-09	4.00E-10
3.6	2.51E-09	1.52E-10	9.04E-10	2.42E-09	4.53E-10
3.7	2.55E-09	1.58E-10	9.20E-10	2.59E-09	5.09E-10
3.8	2.60E-09	1.63E-10	9.35E-10	2.77E-09	5.70E-10
3.9	2.64E-09	1.69E-10	9.49E-10	2.95E-09	6.34E-10
4.0	2.68E-09	1.74E-10	9.63E-10	3.12E-09	7.03E-10
4.1	2.71E-09	1.79E-10	9.76E-10	3.30E-09	7.75E-10
4.2	2.75E-09	1.84E-10	9.89E-10	3.48E-09	8.51E-10
4.3	2.78E-09	1.89E-10	1.00E-09	3.66E-09	9.30E-10
4.4	2.82E-09	1.94E-10	1.01E-09	3.84E-09	1.01E-09
4.5	2.85E-09	1.99E-10	1.03E-09	4.01E-09	1.10E-09
4.6	2.88E-09	2.04E-10	1.04E-09	4.19E-09	1.19E-09
4.7	2.91E-09	2.08E-10	1.05E-09	4.36E-09	1.29E-09
4.8	2.94E-09	2.13E-10	1.06E-09	4.53E-09	1.38E-09
4.9	2.96E-09	2.17E-10	1.07E-09	4.70E-09	1.49E-09
5.0	2.99E-09	2.21E-10	1.08E-09	4.87E-09	1.59E-09

TABLE III, Cont'd

ALI/NRL EXCITATION/IONIZATION RATES (1/SEC)

TEMP	6	7	8	9	10
.1	5.44E-19	3.80E-25	2.57E-14	2.37E-50	0.
.2	6.28E-14	5.37E-17	1.18E-11	2.63E-29	0.
.3	3.92E-12	1.67E-14	9.39E-11	5.01E-22	0.
.4	3.19E-11	3.90E-13	2.67E-10	1.07E-18	0.
.5	1.13E-10	2.63E-12	5.04E-10	1.50E-16	7.24E-23
.6	2.64E-10	9.46E-12	7.73E-10	4.12E-15	3.14E-20
.7	4.84E-10	2.37E-11	1.05E-09	4.48E-14	1.61E-18
.8	7.61E-10	4.75E-11	1.33E-09	2.71E-13	2.88E-17
.9	1.08E-09	8.10E-11	1.60E-09	1.11E-12	2.66E-16
1.0	1.43E-09	1.25E-10	1.85E-09	3.48E-12	1.57E-15
1.1	1.79E-09	1.77E-10	2.09E-09	8.89E-12	6.69E-15
1.2	2.16E-09	2.37E-10	2.32E-09	1.96E-11	2.24E-14
1.3	2.53E-09	3.04E-10	2.53E-09	3.85E-11	6.26E-14
1.4	2.89E-09	3.75E-10	2.73E-09	6.85E-11	1.51E-13
1.5	3.24E-09	4.50E-10	2.91E-09	1.14E-10	3.25E-13
1.6	3.58E-09	5.28E-10	3.09E-09	1.78E-10	6.56E-13
1.7	3.91E-09	6.07E-10	3.25E-09	2.64E-10	1.15E-12
1.8	4.23E-09	6.87E-10	3.40E-09	3.77E-10	1.96E-12
1.9	4.53E-09	7.68E-10	3.54E-09	5.18E-10	3.16E-12
2.0	4.82E-09	8.48E-10	3.67E-09	6.92E-10	4.86E-12
2.1	5.09E-09	9.27E-10	3.79E-09	9.01E-10	7.20E-12
2.2	5.35E-09	1.01E-09	3.91E-09	1.15E-09	1.03E-11
2.3	5.59E-09	1.08E-09	4.01E-09	1.43E-09	1.43E-11
2.4	5.83E-09	1.16E-09	4.11E-09	1.75E-09	1.93E-11
2.5	6.05E-09	1.23E-09	4.21E-09	2.12E-09	2.55E-11
2.6	6.26E-09	1.30E-09	4.29E-09	2.52E-09	3.30E-11
2.7	6.46E-09	1.37E-09	4.38E-09	2.96E-09	4.20E-11
2.8	6.65E-09	1.44E-09	4.45E-09	3.45E-09	5.26E-11
2.9	6.83E-09	1.50E-09	4.53E-09	3.97E-09	6.48E-11
3.0	7.00E-09	1.57E-09	4.60E-09	4.55E-09	7.89E-11
3.1	7.16E-09	1.63E-09	4.66E-09	5.13E-09	9.49E-11
3.2	7.31E-09	1.69E-09	4.72E-09	5.77E-09	1.13E-10
3.3	7.45E-09	1.75E-09	4.78E-09	6.44E-09	1.33E-10
3.4	7.59E-09	1.80E-09	4.83E-09	7.15E-09	1.55E-10
3.5	7.72E-09	1.86E-09	4.88E-09	7.89E-09	1.80E-10
3.6	7.84E-09	1.91E-09	4.93E-09	8.66E-09	2.07E-10
3.7	7.96E-09	1.96E-09	4.97E-09	9.46E-09	2.36E-10
3.8	8.07E-09	2.01E-09	5.01E-09	1.03E-08	2.68E-10
3.9	8.18E-09	2.05E-09	5.05E-09	1.11E-08	3.02E-10
4.0	8.28E-09	2.10E-09	5.09E-09	1.20E-08	3.39E-10
4.1	8.37E-09	2.14E-09	5.12E-09	1.29E-08	3.78E-10
4.2	8.46E-09	2.18E-09	5.15E-09	1.38E-08	4.20E-10
4.3	8.55E-09	2.22E-09	5.18E-09	1.48E-08	4.64E-10
4.4	8.63E-09	2.26E-09	5.21E-09	1.58E-08	5.11E-10
4.5	8.71E-09	2.30E-09	5.24E-09	1.67E-08	5.60E-10
4.6	8.78E-09	2.33E-09	5.26E-09	1.77E-08	6.12E-10
4.7	8.85E-09	2.37E-09	5.28E-09	1.87E-08	6.67E-10
4.8	8.92E-09	2.40E-09	5.31E-09	1.98E-08	7.24E-10
4.9	8.98E-09	2.43E-09	5.33E-09	2.08E-08	7.83E-10
5.0	9.04E-09	2.46E-09	5.34E-09	2.18E-08	8.45E-10

TABLE III, Cont'd

ALI/URL EXCITATION/IONIZATION RATES (1/SEC)

TEMP	11	12	13	14	15
.1	7.49E-38	3.90E-41	2.43E-57	5.09E-65	4.17E-49
.2	5.29E-23	4.19E-25	9.45E-33	3.50E-37	4.53E-29
.3	5.23E-18	1.02E-19	1.59E-24	7.10E-28	2.18E-22
.4	1.73E-15	5.27E-17	2.11E-20	3.24E-23	4.88E-19
.5	5.80E-14	2.30E-15	6.31E-18	2.04E-20	5.12E-17
.6	6.12E-13	2.92E-14	2.82E-16	1.49E-18	1.16E-15
.7	3.33E-12	1.81E-13	4.26E-15	3.21E-17	1.10E-14
.8	1.19E-11	7.21E-13	3.26E-14	3.20E-16	6.00E-14
.9	3.23E-11	2.13E-12	1.58E-13	1.91E-15	2.27E-13
1.0	7.18E-11	5.09E-12	5.60E-13	7.98E-15	6.66E-13
1.1	1.36E-10	1.04E-11	1.57E-12	2.57E-14	1.62E-12
1.2	2.39E-10	1.91E-11	3.71E-12	6.78E-14	3.41E-12
1.3	3.79E-10	3.19E-11	7.67E-12	1.54E-13	6.46E-12
1.4	5.63E-10	4.96E-11	1.43E-11	3.12E-13	1.12E-11
1.5	7.94E-10	7.30E-11	2.44E-11	5.72E-13	1.82E-11
1.6	1.07E-09	1.03E-10	3.89E-11	9.74E-13	2.79E-11
1.7	1.39E-09	1.39E-10	5.88E-11	1.55E-12	4.08E-11
1.8	1.76E-09	1.81E-10	8.47E-11	2.35E-12	5.74E-11
1.9	2.17E-09	2.31E-10	1.17E-10	3.41E-12	7.81E-11
2.0	2.62E-09	2.87E-10	1.57E-10	4.75E-12	1.03E-10
2.1	3.10E-09	3.50E-10	2.05E-10	6.42E-12	1.34E-10
2.2	3.61E-09	4.20E-10	2.60E-10	8.43E-12	1.69E-10
2.3	4.15E-09	4.95E-10	3.25E-10	1.08E-11	2.10E-10
2.4	4.71E-09	5.77E-10	3.94E-10	1.35E-11	2.57E-10
2.5	5.29E-09	6.64E-10	4.73E-10	1.67E-11	3.10E-10
2.6	5.89E-09	7.55E-10	5.59E-10	2.02E-11	3.69E-10
2.7	6.49E-09	8.52E-10	6.52E-10	2.41E-11	4.35E-10
2.8	7.11E-09	9.53E-10	7.55E-10	2.83E-11	5.06E-10
2.9	7.73E-09	1.06E-09	8.59E-10	3.30E-11	5.85E-10
3.0	8.35E-09	1.17E-09	9.71E-10	3.80E-11	6.70E-10
3.1	8.98E-09	1.28E-09	1.09E-09	4.33E-11	7.61E-10
3.2	9.60E-09	1.39E-09	1.21E-09	4.90E-11	8.59E-10
3.3	1.02E-08	1.51E-09	1.34E-09	5.49E-11	9.64E-10
3.4	1.08E-08	1.62E-09	1.47E-09	6.12E-11	1.08E-09
3.5	1.14E-08	1.74E-09	1.61E-09	6.77E-11	1.19E-09
3.6	1.20E-08	1.86E-09	1.74E-09	7.45E-11	1.32E-09
3.7	1.26E-08	1.99E-09	1.88E-09	8.14E-11	1.45E-09
3.8	1.32E-08	2.11E-09	2.03E-09	8.86E-11	1.59E-09
3.9	1.38E-08	2.23E-09	2.17E-09	9.60E-11	1.73E-09
4.0	1.43E-08	2.36E-09	2.32E-09	1.04E-10	1.88E-09
4.1	1.49E-08	2.48E-09	2.47E-09	1.11E-10	2.04E-09
4.2	1.54E-08	2.60E-09	2.61E-09	1.91E-10	2.20E-09
4.3	1.60E-08	2.73E-09	2.76E-09	1.27E-10	2.37E-09
4.4	1.65E-08	2.85E-09	2.91E-09	1.35E-10	2.54E-09
4.5	1.70E-08	2.97E-09	3.06E-09	1.43E-10	2.73E-09
4.6	1.74E-08	3.09E-09	3.21E-09	1.51E-10	2.91E-09
4.7	1.79E-08	3.21E-09	3.36E-09	1.59E-10	3.11E-09
4.8	1.84E-08	3.33E-09	3.50E-09	1.67E-10	3.30E-09
4.9	1.88E-08	3.45E-09	3.65E-09	1.76E-10	3.51E-09
5.0	1.92E-08	3.56E-09	3.79E-09	1.84E-10	3.72E-09

TABLE III, Cont'd

ALI/NRL EXCITATION/IONIZATION RATES (1/SEC)

TEMP	16	17	18	19	20
.1	7.79E-78	0.	3.42E-14	1.27E-17	1.37E-15
.2	1.92E-43	6.84E-50	1.81E-12	2.76E-14	1.99E-12
.3	6.14E-32	2.16E-36	8.20E-12	4.15E-13	2.62E-11
.4	3.65E-26	1.18E-29	1.94E-11	1.74E-12	1.04E-10
.5	1.09E-22	1.29E-25	3.45E-11	4.31E-12	2.51E-10
.6	2.32E-20	6.50E-23	5.31E-11	8.10E-12	4.69E-10
.7	1.08E-18	5.23E-21	7.46E-11	1.50E-11	7.56E-10
.8	1.96E-17	1.44E-19	9.85E-11	1.86E-11	1.10E-09
.9	1.88E-16	1.89E-18	1.24E-10	2.50E-11	1.51E-09
1.0	1.15E-15	1.49E-17	1.52E-10	3.17E-11	1.96E-09
1.1	5.13E-15	8.04E-17	1.80E-10	3.88E-11	2.46E-09
1.2	1.79E-14	3.26E-16	2.09E-10	4.60E-11	2.99E-09
1.3	5.17E-14	1.08E-15	2.39E-10	5.32E-11	3.56E-09
1.4	1.29E-13	3.01E-15	2.68E-10	6.05E-11	4.15E-09
1.5	2.86E-13	7.50E-15	2.98E-10	6.76E-11	4.77E-09
1.6	5.76E-13	1.59E-14	3.27E-10	7.46E-11	5.40E-09
1.7	1.07E-12	3.10E-14	3.55E-10	8.15E-11	6.06E-09
1.8	1.86E-12	5.82E-14	3.85E-10	8.82E-11	6.72E-09
1.9	3.07E-12	1.01E-13	4.10E-10	9.46E-11	7.40E-09
2.0	4.81E-12	1.65E-13	4.35E-10	1.01E-10	8.09E-09
2.1	7.25E-12	2.59E-13	4.62E-10	1.07E-10	8.78E-09
2.2	1.05E-11	3.90E-13	4.86E-10	1.13E-10	9.48E-09
2.3	1.49E-11	5.67E-13	5.09E-10	1.18E-10	1.02E-08
2.4	2.04E-11	7.99E-13	5.35E-10	1.24E-10	1.09E-08
2.5	2.74E-11	1.10E-12	5.53E-10	1.29E-10	1.16E-08
2.6	3.59E-11	1.47E-12	5.73E-10	1.34E-10	1.23E-08
2.7	4.62E-11	1.93E-12	5.93E-10	1.38E-10	1.30E-08
2.8	5.86E-11	2.49E-12	6.11E-10	1.43E-10	1.37E-08
2.9	7.30E-11	3.16E-12	6.29E-10	1.47E-10	1.44E-08
3.0	8.99E-11	3.95E-12	6.46E-10	1.51E-10	1.51E-08
3.1	1.09E-10	4.87E-12	6.62E-10	1.55E-10	1.58E-08
3.2	1.31E-10	5.92E-12	6.77E-10	1.59E-10	1.65E-08
3.3	1.56E-10	7.12E-12	6.92E-10	1.62E-10	1.72E-08
3.4	1.84E-10	8.48E-12	7.06E-10	1.65E-10	1.79E-08
3.5	2.15E-10	1.00E-11	7.19E-10	1.69E-10	1.85E-08
3.6	2.49E-10	1.17E-11	7.31E-10	1.72E-10	1.92E-08
3.7	2.87E-10	1.36E-11	7.43E-10	1.75E-10	1.99E-08
3.8	3.28E-10	1.57E-11	7.54E-10	1.77E-10	2.06E-08
3.9	3.73E-10	1.79E-11	7.64E-10	1.80E-10	2.12E-08
4.0	4.21E-10	2.04E-11	7.74E-10	1.82E-10	2.19E-08
4.1	4.73E-10	2.30E-11	7.84E-10	1.85E-10	2.25E-08
4.2	5.29E-10	2.59E-11	7.92E-10	1.87E-10	2.32E-08
4.3	5.89E-10	2.90E-11	8.01E-10	1.89E-10	2.38E-08
4.4	6.53E-10	3.23E-11	8.09E-10	1.91E-10	2.44E-08
4.5	7.21E-10	3.58E-11	8.16E-10	1.93E-10	2.51E-08
4.6	7.93E-10	3.95E-11	8.23E-10	1.95E-10	2.57E-08
4.7	8.69E-10	4.34E-11	8.30E-10	1.97E-10	2.63E-08
4.8	9.49E-10	4.76E-11	8.36E-10	1.98E-10	2.69E-08
4.9	1.03E-09	5.20E-11	8.42E-10	2.00E-10	2.75E-08
5.0	1.12E-09	5.66E-11	8.48E-10	2.01E-10	2.81E-08

2. The temperature loss due to energy redistribution among increased electron density resulting from collisional ionization reactions - and the inverse.

3. The energy loss due to ionization. The mean ionization energy E_B is evaluated continuously as the specie concentrations vary.

4. The heating due to the applied electric field ξ(volt/cm) is taken as

$$\left(\frac{dT_e}{dt}\right)_\xi = \frac{e\xi u}{(3/2k)} = \frac{e^2\xi^2}{3/2mk\nu_m} = 1.36\text{x}10^{19}\ \frac{\xi^2}{\nu_m}\ (^oK/sec)$$

where u is the electron drift velocity and ν_m is the momentum transfer frequency (sec^{-1}). Values of ν_m are from Ref. 8, reproduced here as Table V.

5. The heating due to the ionizing source

$$\left(\frac{dT_e}{dt}\right)_{source} = \frac{\mu_q}{3/2n_e k}\ q(t) = 58{,}400\frac{q(t)}{n_e}\ (^oK/sec),$$

where μ_q is the energy deposited in electrons per ion pair created, taken to be 7.55eV from the discussion of page 6 above.

The electron energy swarm equation is then solved simultaneously with the concentration equations, and the gas temperature T_A is obtained from energy conservation, using specific heats as specified on the Specie cards described in 2.1.1 above.

TABLE IV

RELAXATION TIMES/SPECIE- (SEC/CC)

REACTION	SPECIE	T= 4.0	6.0	8.0	10.0	12.0
ELASTIC	N2	4.24E+11	2.67E+11	2.04E+11	1.76E+11	1.63E+11
ELASTIC	O2	8.45E+11	6.70E+11	5.90E+11	5.41E+11	5.05E+11
ELASTIC	N	6.77E+11	4.66E+11	3.62E+11	3.00E+11	2.59E+11
ELASTIC	O	1.03E+12	7.26E+11	5.69E+11	4.73E+11	4.09E+11
ROTATIONAL	N2	2.85E+11	3.49E+11	4.02E+11	4.50E+11	4.95E+11
ROTATIONAL	O2	1.20E+11	1.47E+11	1.70E+11	1.90E+11	2.08E+11
VIBRATION	N2	2.23E+09	6.32E+08	3.98E+08	3.38E+08	3.28E+08
VIBRATION	O2	1.73E+10	1.69E+10	1.87E+10	2.18E+10	2.57E+10
EXCITE 1	N2	7.74E+15	9.78E+12	3.35E+11	4.54E+10	1.10E+10
EXCITE 2	N2	1.26E+19	3.05E+15	4.59E+13	3.61E+12	6.56E+11
EXCITE 1	O2	1.63E+15	1.70E+13	1.68E+12	4.09E+11	1.58E+11
EXCITE 2	O2	1.32E+19	4.73E+15	8.62E+13	7.63E+12	1.50E+12
IONIZATION	N2	8.84E+27	1.98E+21	8.85E+17	8.36E+15	3.64E+14
IONIZATION	O2	2.07E+20	2.10E+16	1.99E+14	1.17E+13	1.72E+12

REACTION	SPECIE	T= 15.0	17.4	23.2	34.8	58.0
ELASTIC	N2	1.53E+11	1.50E+11	1.47E+11	1.39E+11	1.15E+11
ELASTIC	O2	4.54E+11	4.18E+11	3.47E+11	2.55E+11	1.79E+11
ELASTIC	N	2.18E+11	1.96E+11	1.62E+11	1.31E+11	1.21E+11
ELASTIC	O	3.46E+11	3.09E+11	2.53E+11	2.02E+11	1.83E+11
ROTATIONAL	N2	5.51E+11	5.94E+11	6.85E+11	8.39E+11	1.08E+12
ROTATIONAL	O2	2.33E+11	2.51E+11	2.89E+11	3.54E+11	4.58E+11
VIBRATION	N2	3.50E+08	3.86E+08	5.16E+08	9.22E+08	2.33E+09
VIBRATION	O2	3.32E+10	4.05E+10	6.29E+10	1.30E+11	3.65E+11
EXCITE 1	N2	2.75E+09	1.27E+09	3.80E+08	1.14E+08	4.58E+07
EXCITE 2	N2	1.17E+11	4.51E+10	1.00E+10	2.19E+09	6.69E+08
EXCITE 1	O2	6.00E+10	3.50E+10	1.50E+10	6.45E+09	3.50E+09
EXCITE 2	O2	2.90E+11	1.16E+11	2.77E+10	6.52E+09	2.12E+09
IONIZATION	N2	1.55E+13	2.61E+12	1.55E+11	8.02E+09	5.66E+08
IONIZATION	O2	2.44E+11	8.08E+10	1.35E+10	1.93E+09	2.97E+08

T = Temperature (10^3°K)

TABLE V.: Electron collision frequencies per molecule*

ϵ (eV)	N_2	O_2	NO	O	N	H_2O
.005	7.5(-10)		9.7(-9)			2.85(-6)
.007	9.7(-10)		8.0(-9)			2.35(-6)
.01	1.3(-9)		6.7(-9)			1.93(-6)
.015	1.87(-9)		5.7(-9)			1.57(-6)
.02	2.43(-9)	1.2(-9)	5.25(-9)			1.36(-6)
.03	3.53(-9)	1.7(-9)	4.7(-9)	6.0(-9)		1.10(-6)
.05	5.65(-9)	2.8(-9)	4.6(-9)	7.2(-9)		8.5(-7)
.07	7.7(-9)	4.0(-9)	4.9(-9)	8.5(-9)		7.2(-7)
.1	1.10(-8)	5.0(-9)	5.9(-9)	1.02(-8)		6.0(-7)
.15	1.60(-8)	6.5(-9)	9.0(-9)	1.3(-8)		4.85(-7)
.2	2.08(-8)	8.6(-9)	1.4(-8)	1.5(-8)		4.15(-7)
.3	2.90(-8)	1.32(-8)	4.0(-8)	1.8(-8)		3.4(-7)
.5	4.15(-8)	2.16(-8)	1.2(-7)	2.4(-8)	4.3(-9)	2.63(-7)
.7	5.1(-8)	3.05(-8)	1.06(-7)	2.8(-8)	6.2(-9)	2.25(-7)
1.0	6.0(-8)	4.65(-8)	9.5(-8)	3.5(-8)	9.5(-9)	1.93(-7)
1.5	8.7(-8)	5.5(-8)	9.3(-8)	4.4(-8)	1.68(-8)	1.64(-7)
2.0	1.9(-7)	5.75(-8)	9.2(-8)	5.2(-8)	2.55(-8)	1.48(-7)
3	2.2(-7)	6.1(-8)	9.2(-8)	6.6(-8)	4.1(-8)	1.30(-7)
5	1.46(-7)	7.3(-8)	9.6(-8)	9.3(-8)	8.0(-8)	1.17(-7)
7	1.64(-7)	1.02(-7)	1.1(-7)	1.17(-7)	1.03(-7)	1.13(-7)
10	2.08(-7)	1.48(-7)	1.77(-7)	1.52(-7)	1.3(-7)	1.24(-7)
15	2.75(-7)	1.93(-7)	2.6(-7)	2.1(-7)	1.55(-7)	1.74(-7)
20	3.15(-7)	2.2(-7)	1.95(-7)			2.27(-7)
30	3.6(-7)	2.6(-7)	3.4(-7)			2.70(-7)

*1(-7) means 1×10^{-7} cm^3/sec. As indicated in the text and in Figure 21-1 the number of significant figures given is not a measure of the reliability of the data.

3.0 RESULTS

We report here some results from seven cases studied.

Problem Number One:

An instantaneous pulse of ionizing radiation at time $t = 0$ and no external electric field,

$$q(t) = 7.3\times10^{17}\delta(t)\frac{eV}{cm^3 sec} = 1.2\times10^{6}\delta(t)\frac{erg}{cm^3 sec} .$$

This source results in $n_e(0) = 2.16\times10^{16}$ electrons/cm^3 at $t = 0$ at an electron temperature of 58,400°K and a final equilibrated gas temperature of ~400°. The time-dependence of the electron temperature is illustrated in Figure 1. The electron concentration (relative to $n_e(0)$) and conductivity, $\sigma(sec^{-1})$, are given in Figure 2, where

$$\sigma(sec^{-1}) = \frac{e^2 n_e \nu_m}{m(\omega^2+\nu_m^2)} = 6.43\times10^{6}\frac{n_e(cm^{-3})}{\nu_m(sec^{-1})}$$

for $\omega << \nu_m$, the momentum transfer collision frequency, discussed in Section 2.1.3 above.

The electron concentration in relative units -- as in Figure 2 -- is a fair approximation for other doses, up to values large enough that the final equilibrated gas temperature is several thousand degrees. In Figure 2 we also present results of a single temperature calculation, with the significantly lower electron concentration at early times.

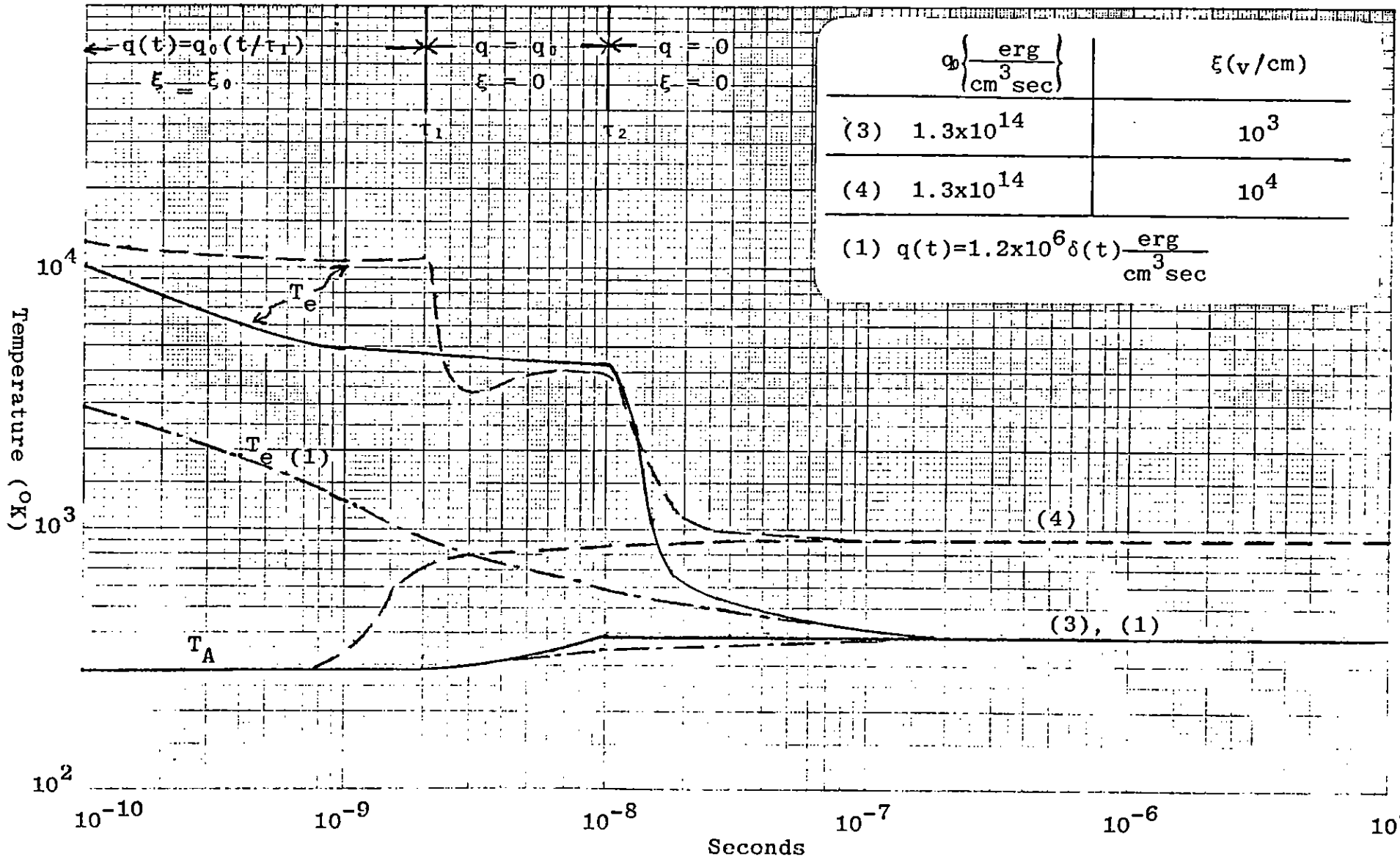

Figure 1: Electron temperature T_e, gas temperature T_A vs. time.

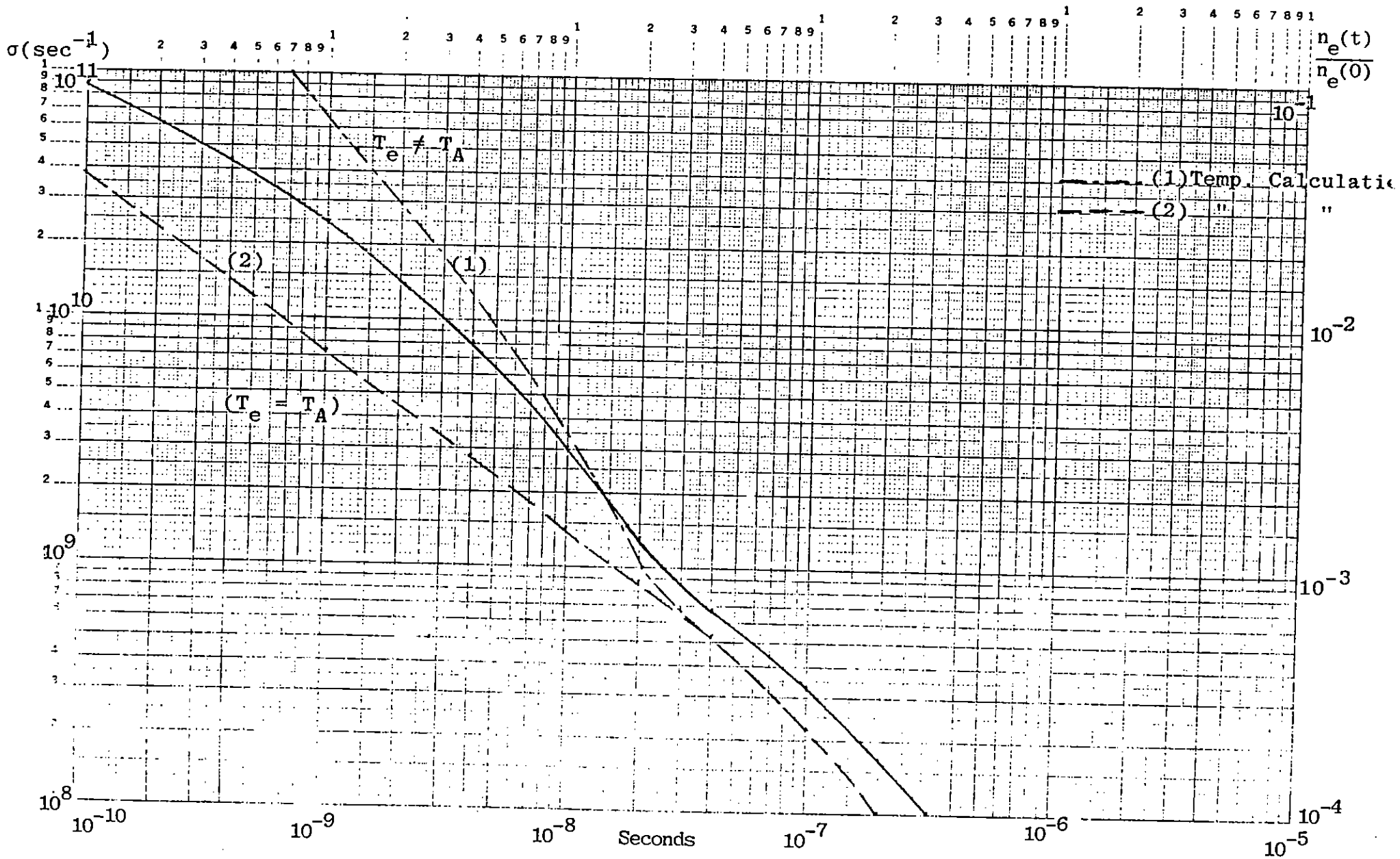

Figure 2: Conductivity $\sigma(sec^{-1})$ and relative electron concentration from an instantaneous pulse of ionizing radiation, $q(t)=7.3\times10^{17}\delta(t)\frac{eV}{cm^3}$.

From consideration of Table V, it is clear that the low temperature momentum transfer frequency is dominated by water if the water vapor concentration is sufficiently high. For example, at 75% relative humidity in ambient sea level air, the contributions of H_2O and N_2 to ν_m are roughly equal near $kT_e = 0.07eV$ or $T_e \sim 800^oK$, and at lower temperatures water dominates. Thus, the dominant effect of water vapor on the low temperature conductivity may be easily accounted for -- decreasing the conductivity according to Table V.

Less easy to treat is the ξ-field heating term in the electron energy swarm equation -- increasing the water vapor content corresponds to a slightly weaker field at low temperatures. In practice, however, when the ξ-field is important the electron temperature remains high enough so that the sensitivity to water vapor is unimportant.

Finally, the long term persistence of relatively high concentrations of O_3, NO and NO_2 is important. At 10^{-5} sec, when $T_e = T_A = 394^oK$, practically none of these species would be expected in KTE. Even for the small dose treated here, however, we find:

$$(O_3) = 1.5 \times 10^{16}/cm^3$$
$$(NO) = 5.5 \times 10^{15}$$
$$(NO_2) = 9.3 \times 10^{14}$$

For problems numbered 2-7 the source and field are taken to be

$$q(t) = q_0\,(t/\tau_1), \qquad (t \leq \tau_1)$$
$$= q_0, \qquad (\tau_1 \leq t \leq \tau_2)$$
$$= 0, \qquad (t > \tau_2)$$

and $$\xi(t) = \xi_0, \qquad (t \leq \tau_1)$$
$$= 0, \qquad (t > \tau_1)$$

with $\tau_1 = 2\text{x}10^{-9}$sec and $\tau_2 = 10^{-8}$sec.

Problem Two:

$$q_0 = 8.1\text{x}10^{25}\left(\frac{\text{eV}}{\text{cm}^3\text{sec}}\right) = 1.3\text{x}10^{14}\left(\frac{\text{erg}}{\text{cm}^3\text{sec}}\right)$$

$$\xi_0 = 0 \quad , \; Q = \int_0^\infty q(t)dt = 1.2\text{x}10^{6}\text{erg/cm}^3 \quad .$$

Problem Three:

Same as problem two except $\xi_0 = 10^3$v/cm. Results of problems two and three are only insignificantly different. The electron and gas temperatures, T_e and T_A, respectively, are presented in Figure 1 (solid line). Thus, the electron temperature is driven by the source, not the field -- for the chosen values. The conductivity, $\sigma(\text{sec}^{-1})$, is given in Figure 3.

Problem Four:

Same as problem three except $\xi_0 = 10^4$v/cm. The temperatures are in Figure 1 (dashed line) and the conductivity in Figure 3. For this field strength, the electron temperature is dominated by terms (3) and (4) of the energy swarm equation --

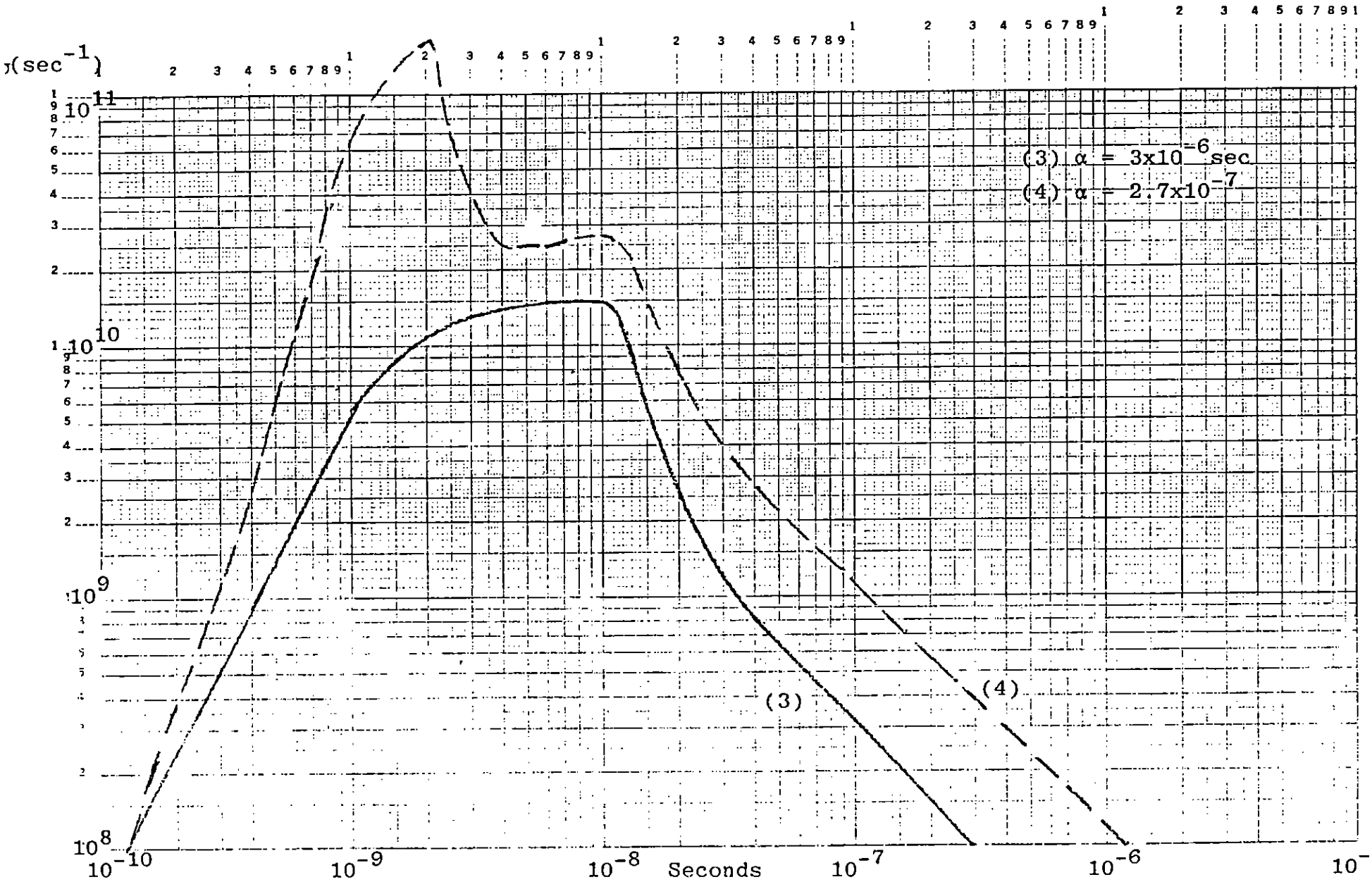

Figure 3: Conductivity $\sigma(sec^{-1})$ vs. time.
(Note: for $\sigma < 10^{8} sec^{-1}$, $\sigma(t) \propto e^{-t/\alpha}$)

balancing the field heating against the loss due to collisional ionization. The result is an approximately constant electron temperature of ~11,000° and a roughly constant electron production rate and rapidly rising conductivity until the field is turned off at $t = 2\times10^{-9}$sec, after which the solutions quickly approach the field-free case, except for the larger gas temperature obtained. The energy added by the field is $6.1\times10^{6}\text{erg/cm}^3$.

Problem Five:

$$q_0 = 8.1\times10^{26}\left(\frac{\text{eV}}{\text{cm}^3\text{sec}}\right) = 1.3\times10^{14}\left(\frac{\text{erg}}{\text{cm}^3\text{sec}}\right)$$

$$Q = \int_0^\infty q(t)dt = 1.2\times10^{7}\text{erg/cm}^3$$

$$\xi_0 = 0 \quad .$$

Problem Six:

Same as problem five except $\xi_0 = 10^3$v/cm. Again, the results of problem five and six are essentially the same. Temperatures are in Figure 4 (solid line) and the conductivity in Figure 5.

Problem Seven:

Same as problem six except $\xi_0 = 10^4$v/cm. The same remarks apply here as did to problem four -- only the numerical values differ. The total energy added by the field is $1.24\times10^{7}\text{erg/cm}^3$

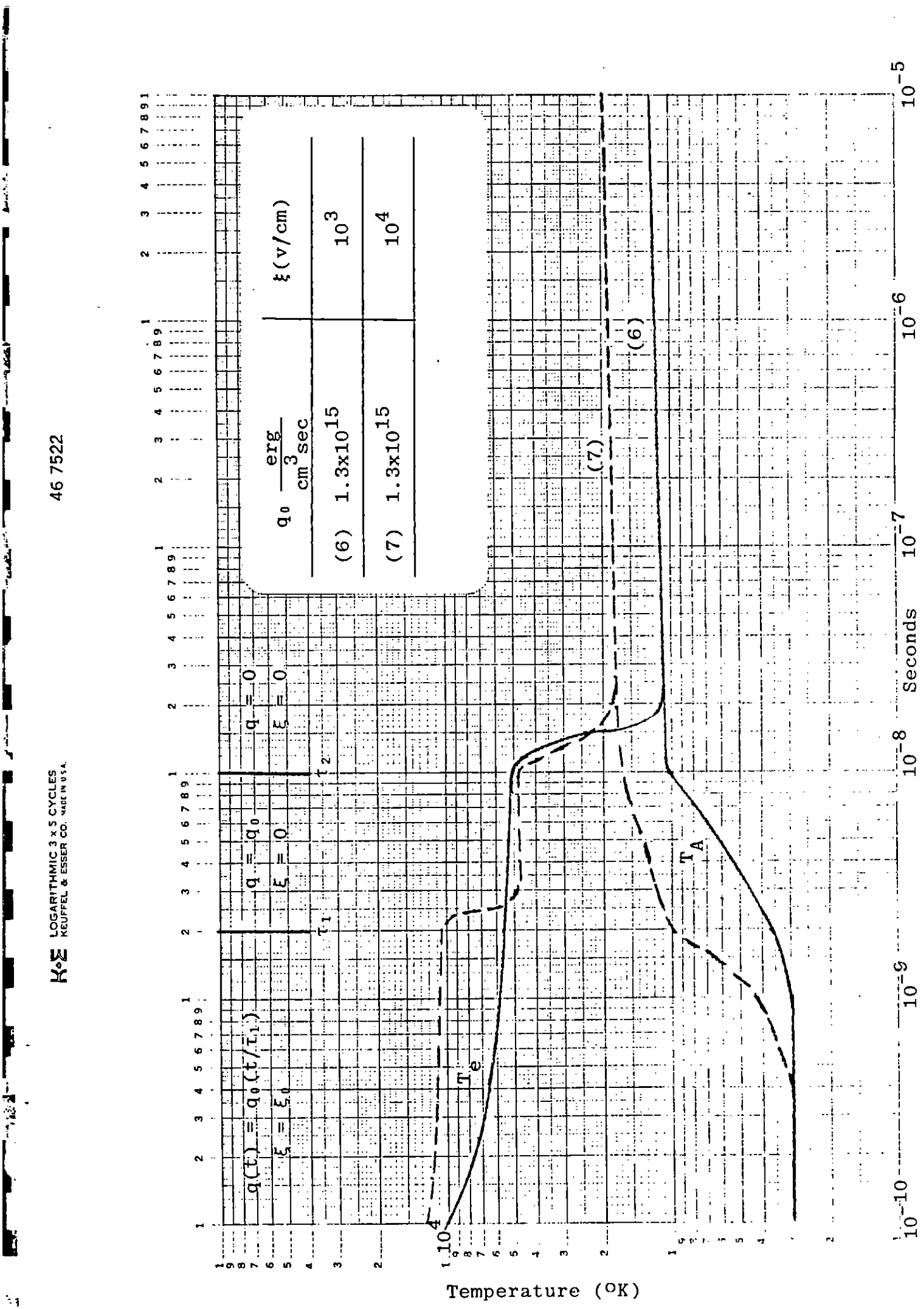

Figure 4: Electron temperature T_e, gas temperature T_A vs. time.

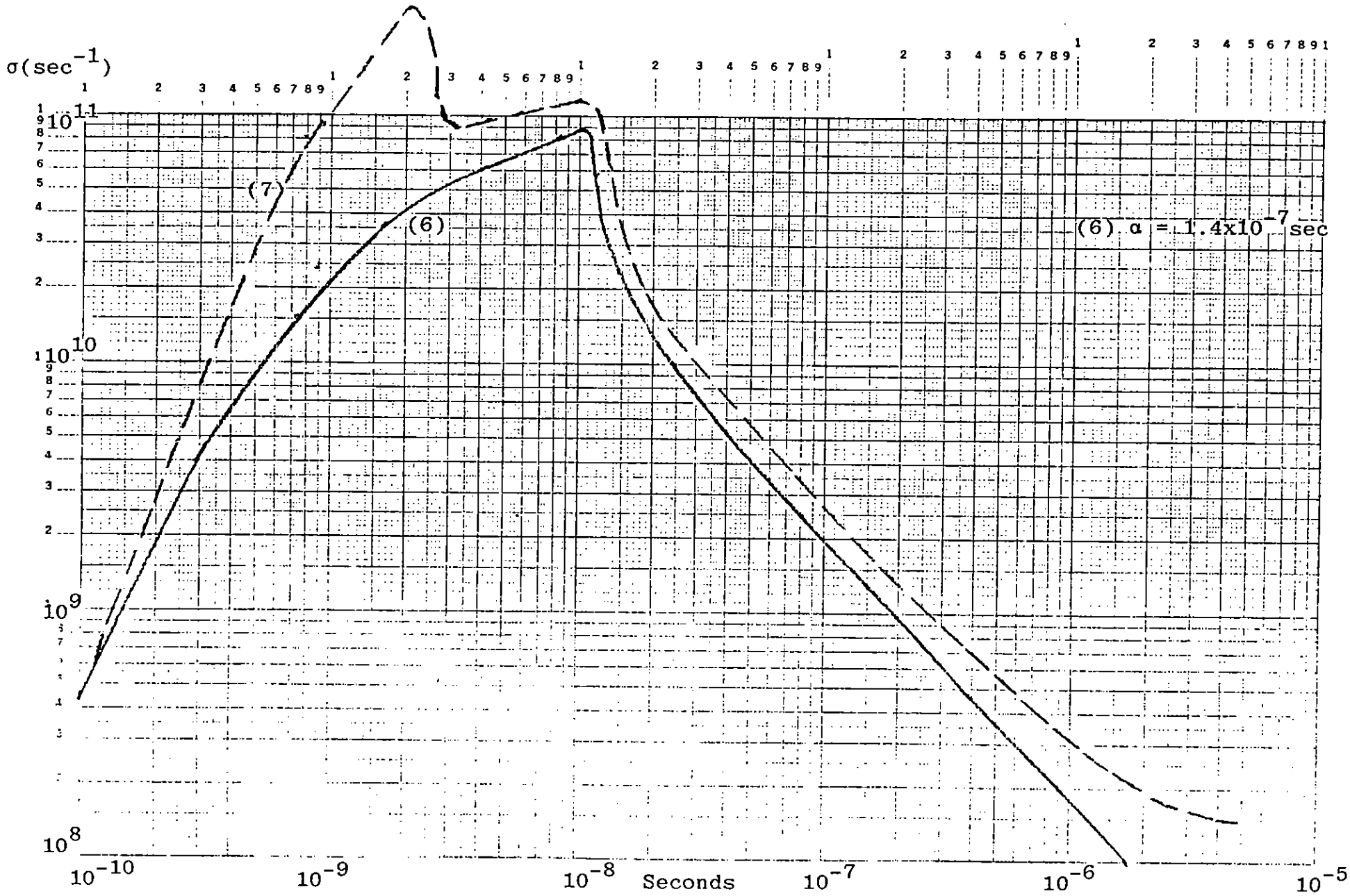

Figure 5: Conductivity (sec^{-1}) vs. time.
(Note: for $\sigma<10^{-8}$sec^{-1}, $\sigma(t) \propto e^{-t/\alpha}$)

4.0 CONCLUSIONS

Results such as those we have summarized here are useful in delimiting domains of applicability of simpler electron temperature models -- such as field-driven, source-driven, and instantaneous -- and the time dependence of deviations therefrom. The detailed specie concentrations we have obtained may be useful to estimate spectral radiant emissions from air perturbed in such a fashion.

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