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LEVEL III

DNA 1948H
Rev. 7

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SPECIAL NOTICES TO ALL HANDBOOK USERS

1) The contents of Appendices A, E, F, and G, and of the Acknowledgments at the front of the Handbook are several years old and therefore outdated with respect to chapter revisions issued recently. Further such revisions will be issued in the near future. These will generate additional changes in the Appendices. It has therefore been determined that final revision of the Appendices will await completion of those chapter revisions now in progress.

2) The chemical kinetics data tabulated in Chapter 24 (transmitted herewith) supersedes much of the information in Chapters 10-21. Forthcoming revisions of some of these chapters may in turn supersede portions of Chapter 24. The user is therefore cautioned to do his own cross-checking within the Handbook, paying particular attention to the dates of issue of materials which appear to conflict with one another on any given datum.

3) In view of the above statements, if at any time you should require reference information which is inadequately covered in one of the outdated Appendices, or clarification as to the "latest" rate data where a rapidly advancing state of the art has left you in doubt on a given reaction, you may write or telephone either of the editors for assistance, as follows:

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MEMORANDUM

To : All Recipients of the DNA Reaction Rate Handbook (DNA 1948H)

From : The Editors

Subject: Revision Number 7

Enclosed is a copy of Revision Number 7 to the Handbook. It is a complete rewrite and recompilation of Chapter 24, "Summary of Suggested Rate Constants."

Please note especially the following two points regarding this particular revision:

(1) The revision effort, which began with an advisory group meeting at the University of Pittsburgh on March 30, 1976, has taken nearly two years, during which it has been necessary to cycle and recycle the recommendations of the attendees at that meeting back through the group and to consult with others concerning the validity and currency of many of the recommended data in the chapter. The result is considered to be the best possible one for DNA purposes as of March 1978. However, it should be borne in mind that this chapter, perhaps more than any other in the Handbook, represents only the interim status of a vigorously ongoing scientific effort.

(2) It is vital that all Handbook users now read the rewritten text of Chapter 24 because important changes have been made in the format of the data presentation in Table 24-1, and these are explained in detail at the beginning of the chapter. A thorough understanding of this material will enable the user to make the most effective possible use of the table. To repeat, PLEASE READ THESE NEW INTRODUCTORY PORTIONS OF THE CHAPTER, — NOW!!

As with previous revisions you should immediately discard the prior version of Chapter 24 and replace it with the enclosed material. You should also enter on page iii of your Handbook the following information: Revision Number 7, Date of Issue - June 1978; Date of Receipt - whatever day you receive this; and sign your name in the last column.

Revision Number 8 is expected to comprise a rewriting of Chapter 8 and an updating of Chapter 11, according to present plans. The anticipated issuance should take place in several months.

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LEVEL III

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(6) DEFENSE NUCLEAR AGENCY

REACTION RATE HANDBOOK,

SECOND EDITION. Revision No. 7.

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24. SUMMARY OF SUGGESTED RATE CONSTANTS*

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M.H. Bortner, General Electric Company
(Latest Revision 1 March 1978)

24.1 INTRODUCTION

This chapter presents a tabulated summary of reactions, with suggested rate coefficients, relevant to the problems of atmospheric chemical recovery following a perturbation. The present generation of computers permits the convenient handling of large numbers of reactions in the solution of such problems. Thus, one can now include in detailed calculations of this type hundreds of individual reactions and follow the complete histories of large numbers of individual species as atmospheric constituents. Many computer codes exist which have been designed for the study of atmospheric systems, and which are capable of carrying out the appropriate calculations. Such codes are in use at various institutes and laboratories throughout the country. In order to promote cooperation among these installations, it is desirable to have standard rate coefficients which are recognized universally as valid for all common purposes, e.g., the comparative solution of test problems, or the complementary solution of different aspects of a given large problem.

It is conceded at the outset that not all the reactions listed are universally important in all coded systems under all conditions. By the same token, some reactions which might not seem to have a direct bearing on a given system can he significant indirectly, either contributing to, or acting as precursors of, other processes which are influential within the given context. Furthermore, there probahly are some important omissions from the table, since reactions not yet thought to play any significant role in atmospheric deionization mechanisms, or perhaps not yet even conceived of, might be found in the future to be quite significant in some context or scheme still to be considered or devised.

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*The authors are pleased to acknowledge that Dr. R.H. Kummler of Wayne State University was an active contributor to earlier versions of this chapter.

24.2 PRESENTATION OF REACTIONS AND RATE DATA

24.2.1 Listing of Reactions

The reactions are listed in Table 24-1 by type, in an order consistent with the listing of reaction types in Chapter 6 (Table 6-1). For each reaction type, i.e., within each section of Table 24-1, reactions are usually listed according to the identity of the reactant species ranked according to the following "priority" order: oxygen, nitrogen, hydrogen, carbon, metals. This order is followed, respectively and in sequence, for monatomic, diatomic, triatomic, polyatomic, and complex or clustered species. Where one of the reactants is an ion, it is the atomic composition of the ionic reactant which will determine the order of listing; where two ions interact, it is the composition of the positive ion which will determine the order of listing.

For reactant or product species known to participate in a given reaction in an excited electronic state or vibrational mode, appropriate designations are appended to the appropriate species formula. Corresponding ground-state designations are sometimes noted for contrast, e.g., where both ground and excited states of the same species are used or produced in essentially the same reaction. However, most reactions carry no state designations for any of the species involved. Species in these instances usually can be construed as being either in a Boltzmann distribution of states or in the ground state. The sources are usually indefinite on this point since modern investigative methods are not yet always keyed to the complete state analysis of all participating species in all reactions studied, and this summary can be no more definitive than its source material.

24.2.2 Data Format

In Table 24-1, the rate coefficients are presented in cgs units, i.e., in sec^{-1}, $cm^3 sec^{-1}$, and $cm^6 sec^{-1}$ for one-, two-, and three-body processes, respectively. Species densities are in cm^{-3} and temperature is in K. The letter "M" is used to represent a collision partner; unless specifically noted otherwise, it represents any possible species present and acting as a catalyst. The numerical notation [-x] signifies multiplication by 10^{-x}. Most rate functions "k" are represented by sets of numbers "a", "b", and "c", which refer in turn to the formulation:

$$k = a(T/300)^b \exp(-c/T),$$

where 300 in the first parenthesized term is the usual reference temperature (in K), unless another T_{ref} is designated in the "Notes" column of the table. A few rate functions found in Sections XXV, XXXII, XXXIV, and XXXV follow a more complex variation with temperature than that given above, or are dependent on other parameters as well, e.g., local species densities. These complex functions are presented in brackets and transcend the usual format of the table. For some reactions listed in Section XXV, the coefficient "a" is itself density-dependent rather than constant.

Wherever the authors of the various chapters (including revisions) of this Handbook have recommended specific values for the reaction rate constants or coefficients, those values are used in Table 24-1 unless they have been superseded by more recent work. In certain instances where the rate data are either uncertain or unavailable, the reactions might nevertheless be considered sufficiently important to be included. Values of these rate constants or coefficients have been estimated, either by an appropriate expert, e.g., a cognizant chapter author, or by a committee of knowledgeable workers. These cases are noted accordingly in the "Sources" column of the table as either a rather good estimate (Est.) or a somewhat shakier "guesstimate" (Gst.). IT IS STRESSED THAT SINCE A SIGNIFICANT NUMBER OF THE REACTIONS LISTED MIGHT BE CHARACTERIZED IN ONE OF THESE FASHIONS, ONE SHOULD BE EXTREMELY CAREFUL NOT TO CONSIDER THESE RATES AS FINAL.

In addition, it should be carefully noted that the listing of a zero (0) value for any rate parameter (viz., "a", "b", or "c") should be taken at face value as a true datum, i.e., the number in question is known to be zero. Where such a parameter is unknown, on the other hand, that fact is indicated by the use of a dash (-). Furthermore, wherever $c \neq 0$, it follows that the rate constant at 300 K, k_{300}, is unequal to the listed value of the "a" parameter; in all such cases k_{300} has been calculated and is listed in the "Notes" column. Such values are not to be construed as implying actual measurement at 300 K, unless specifically so stated in the table. Also, wherever the useful range of reaction temperatures is well beyond 300 K, a value of k_{300} would be meaningless and is, therefore, omitted.

In addition to such standard information items as T_{ref} and k_{300} just mentioned, and experimental temperature ranges (subsection 24.2.3),

the "Notes" column of the table contains explanatory and parametric facts covering a very broad scope. Certain items, which in prior versions of the table were given in footnotes, now have been relegated to a special listing at the end of the table. They are referred to by code letters ("Note a", "Note b", etc.) in the "Notes" column, where appropriate. This has been done to avoid repeating several rather lengthy footnotes, some of which appear more than once in the table.

24.2.3 Temperature Dependence

Temperature dependences designated by means of the "b" and "c" parameters refer in most instances to the ordinary gas-kinetic or translational temperature T or T_{gas}. However, certain reaction rates turn out to depend preferentially upon specialized temperatures, which are here designated accordingly, e.g., the kinetic temperature of interacting electrons (T_e) or ions (T_i), and the vibrational temperature of interacting molecules (T_v) or ions (T_{iv}). (N.B.: All temperatures and temperature dependences are expressed in kelvins (K).) In this connection, several types of special cases should be noted, as well as one or two other points on temperature dependence, viz.:

(1) Section IV of the table includes several instances where the temperature dependence changes, at some threshold in T_{iv}, from a variation in T_e to one in T_{iv}.

(2) Sections XIII and XIV include reactions for which the temperature dependence in T_i is characterized by a different set of kinetic parameters above some designated T_i than below it, i.e., the curve of rate constant as a function of T_i breaks sharply at the stated threshold value.

(3) Section XXVII lists some cases in which alternate sets of kinetic parameters must be used at temperatures in the hundreds of K (for which the mathematical treatment is the same as for any other reaction) or in the thousands of K (for which a T_{ref} different than 300 K — usually 3000 K — is the preferred form, and is so indicated).

(4) The literature reports many reactions for which temperature dependences may be equally well described mathematically as variations in "b" or in "c", but not both. In such cases, the "c"-variant form ordinarily reads like a negative activation energy. Therefore, the "b"-variant form usually has been reported in the table since it is less objectionable conceptually. Nevertheless,

some negative activation energies are also reported as such (in Sections XXVII and XXIX).

(5) Wherever possible, experimental temperature ranges defining the validity of a given set of rate parameters are listed in the "Notes" column. Where these are missing, it should be assumed that the values tabulated are valid at approximately room temperature (300 K) if both "b" and "c" are zero or unknown. Alternatively, if either "b" or "c" is listed as a known value other than zero, validity of the parameters given can be assumed roughly over the order of magnitude of several hundreds of K.

24.2.4 Uncertainties and Error Limits

The significance of the stated limits of uncertainty of most of the rate parameters in Table 24-1 is itself uncertain in that the tabulated limits could have been drawn from any of several different sources, e.g.:

(1) They might reflect experimental error as reported in the original literature citation from which the rate information was obtained.

(2) They might reflect a theoretician's uncertainty based upon the data or the treatment used to derive or estimate a given parameter.

(3) They might simply reflect a good guess or consensus accompanying an estimated rate parameter, and could have been arrived at by a knowledgeable individual or group who might have based the suggested uncertainties upon some handy rule of thumb derived from lengthy personal experience.

(4) If sufficient uncertainty exists, they might not even be listed.

(5) Where the uncertainty is so great that the parameter itself is considered to be unknown, values might not be listed at all and a dash (-) might be inserted at the appropriate location in the table.

24.3 OTHER SOURCES OF RATE DATA

Several more specialized compendia and services are available to the investigator of atmospheric chemical effects phenomenology.

24.3.1 Services of the National Bureau of Standards (NBS)

The National Standard Reference Data System (NSRDS) exists for the purpose of promoting the critical evaluation and dissemination of numerical data of the physical sciences in general. Although this program is coordinated by the Office of Standard Reference Data (OSRD) of NBS, it nevertheless involves the efforts of many groups in a variety of institutions. The primary aim of the program is to provide compilations of critically evaluated numerical data. These tables are published in the Journal of Physical and Chemical Reference Data, the NSRDS-NBS Publication Series of NBS, and through other appropriate channels. NSRDS communicates informally through its Reference Data Report, formerly known as NSRDS News, and subscriptions can be obtained by writing to: OSRD, NBS, Washington, D.C. 20234.

One of the more specialized data centers within the NSRDS system is the Chemical Kinetics Information Center (CKIC). This center maintains and routinely updates a data bank covering the kinetics of collisional and photochemical reactions involving neutral species, as reported in the open literature. In response to requests for current information in its areas of coverage, CKIC provides to the requestor either its own recommended value for a given rate parameter (if such a recommendation has been determined), or the latest and/or most pertinent literature citation available. For the fulfillment of requests of "substantial" magnitude, a charge might be levied for this service, at the discretion of CKIC. Requests should be directed to: Dr. Robert F. Hampson, Director, CKIC, NBS, Washington, D.C. 20234.

Another activity of NSRDS is the Radiation Chemistry Data Center (RCDC), Radiation Laboratory, University of Notre Dame, Notre Dame, Indiana 46556. RCDC publishes a Biweekly List of Papers on Radiation Chemistry which provides current bibliographical material in ten categories, selected for relevance to radiation chemistry, but often quite useful in atmospheric chemical kinetics as well. The material is derived from a scanning of about 50 journals as well as Chemical Abstracts and other publications which

list current references. A subscription, currently $21 per year (domestic delivery) excluding the Annual Indexed Cumulation, is available by application to: NBS Accounting Division, Building 101, Room A836, NBS, Washington, D.C. 20234.

In addition, NSRDS published (1972) a translation (COM-72-10014) by L.J. Holtschlag (edited by R.M. Fristrom) of V.N. Kondratiev's "Rate Constants of Gas Phase Reactions", a reference book of limited applicability to most DNA-oriented problems. It can be purchased through the National Technical Information Service, Springfield, Virginia 22151.

Finally, a summary listing entitled: "Chemical Kinetics Tables, Data Evaluations and Bibliographies. A Guide to the Literature" is available from NBS as NBS List of Publications #73 (revised Sept. 1976). Prepared by J.G. Koch of the CKIC Institute for Materials Research, the list is organized into six sections covering output of NSRDS, CKIC, and other organizations outside NBS. Disappointingly enough, the DNA Reaction Rate Handbook is not listed therein.

24.3.2 Services of the National Oceanic and Atmospheric Administration (NOAA)

The Environmental Research Laboratories (ERL) of NOAA at Boulder, Colorado, have recently announced the forthcoming publication of a compendium of rate parameters. The information provided will be limited to that determined experimentally at NOAA/ERL, and will pertain initially only to ion-neutral reactions, with planned future expansion to include information on ion mobilities and neutral-neutral reactions. Present indications are that the volume of intended coverage will be in excess of 550 ion-neutral reactions, approximately 100 zero-field ion mobilities, and more than 100 neutral-neutral reactions. The tabular format of the compendium will provide information, for each reaction reported, as follows: rate constant (as determined), percent experimental error, product branching ratio (if applicable), experimental energy range (K or eV), experimental method, and open literature citation (if applicable). No format as yet has been announced for the tabulation of ion mobility data. All information will be stored on tape for reproduction by magnetic-memory typewriter. The initial distribution is expected to take place in the near future, with updating planned on an annual basis. Requests for subscription to this service should be addressed to: Dr. Fred C. Fehsenfeld, U.S. Department of Commerce, NOAA, ERL, Boulder, Colorado 80302.

24.3.3 Other Services Available

The Department of Physical Chemistry, University of Leeds, Leeds 2, England, has compiled, analyzed, and reported its recommendations on "High Temperature Reaction Rate Data" in a series of reports prepared under the leadership of Professor D. L. Baulch, to whom any requests for further information should be addressed.

A "Bibliography of Chemical Kinetics and Collision Processes," edited by Adolf R. Hochstim, was published in 1969 by IFI/Plenum Data Corporation, 227 West 17th Street, New York, New York 10011. It provides a useful annotated list of approximately 20,000 literature citations covering the period 1900-1966, including data on reaction rates, cross-sections, and excited-state lifetimes.

Other sources of information can be found among the general references listed in Appendix H of this Handbook.

Table 24-1. Reactions and suggested rate constants.

$$k = a(T/300)^b e^{-c/T}$$

No.	Reaction	a	b	c	Notes	Sources
I. Radiative Recombination:						
1.	$O^+ + e \rightarrow O + h\nu$	$(3.5\pm1.0)[-12]$	(-0.7 ± 0.1)	0		Chp. 16
2.	$N^+ + e \rightarrow N + h\nu$	$(3.5\pm1.0)[-12]$	(-0.7 ± 0.1)	0		Chp. 16
3.	$H^+ + e \rightarrow H + h\nu$	$(3.5\pm1.0)[-12]$	(-0.7 ± 0.1)	0		Chp. 16
4.	$O_2^+ + e \rightarrow O_2 + h\nu$	$(4)[-12\pm1]$	(-0.7 ± 0.5)	0	Note a	Est.
5.	$NO^+ + e \rightarrow NO + h\nu$	$(4)[-12\pm1]$	(-0.7 ± 0.5)	0	Note a	Est.
6.	$N_2^+ + e \rightarrow N_2 + h\nu$	$(4)[-12\pm1]$	(-0.7 ± 0.5)	0	Note a	Est.
II. Photoionization:						
1.a.	$O + h\nu \rightarrow O^+(^4S) + e$	$(2.83\pm0.57)[-7]$	0	0	Note b	Ref. 24-1
b.	$\rightarrow O^+(^2D) + e$					
c.	$\rightarrow O^+(^2P) + e$					
2.	$N + h\nu \rightarrow N^+ + e$	-	-	-	Note c	Chps. 12, 13
3.a.	$O_2 + h\nu \rightarrow O_2^+ + e$	$(5.91\pm1.18)[-7]$	0	0	Note b	Ref. 24-1
b.	$\rightarrow O^+ + e + O$					
c.	$\rightarrow O^+ + e + O(^1D)$					
4.	$O_2(a^1\Delta_g) + h\nu \rightarrow O_2^+ + e$	-	-	-	Note c	Chps. 12, 13
5.	$NO + h\nu \rightarrow NO^+ + e$	$(6.24\pm1.25)[-7]$	0	0	Note b	Ref. 24-1

Table 24-1. (continued)

No.	Reaction	o	b	c	Notes	Sources
II. Photoionization: (continued)						
6.o.	$N_2 + h\nu \rightarrow N_2^+ + e$	(4.22±0.84)[-7]	0	0	Note b	Ref. 24-1
b.	$\rightarrow N^+ + e + N$					
c.	$N^+ + e + N(^2D)$					
7.	$NO_2 + h\nu \rightarrow NO_2^+ + e$	-	-	-	Note c	Chps. 12, 13
III. Three-Body Recombination:						
1.	$X^+ + e + M \rightarrow$ Products	(2)[-27.0±0.2]	(-2.5)	0	X^+=atomic ion and: M = atom	Chp. 16 + Est.
		(6)[-27.0±0.3]	(-2.5)	0	M = molecule	
		(3)[-26.0±0.3]	(-2.5)	0	M = polar molecule	
2.	$X^+ + e + e \rightarrow$ Products	(7±3)[-20]	(-4.5)	0	X^+=any atomic or molecular ion	Chp. 16
3.	$XY^+ + e + M \rightarrow$ Products	(6)[-27.0±0.3]	(-2.5)	0	XY^+=molecular ion and: M = atom or molecule	Chp. 16 + Est.
		(3)[-26.0±0.3]	(-2.5)	0	M = polar molecule	
IV. Dissociative Recombination:						
1.	$O_2^+ + e \rightarrow 1.0\ O(^3P) + 0.9\ O(^1D) + 0.1\ O(^1S)$	(2.1±0.2)[-7]	(-0.02±0.07)	0	$T=T_e$; Notes d, e	Chp. 16 + Est.
2.o.	$NO^+ + e \rightarrow N + O$	(4.0±0.3)[-7]	(-1.0±0.2)	0	T=200-300 K	Chp. 16
b.		(4.0±0.3)[-7]	$\left(-0.4^{+0.2}_{-0.1}\right)$	0	$T=T_e \geq 300$ K; Note f.	Refs. 24-2 through 24-4; cf. Ref. 24-5

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
IV.	Dissociative Recombination: (continued)					
2.c.	$NO^+ + e \rightarrow N(^2D) + O(^3P)$				Note g	Refs. 24-3, 24-6
3.a.	$N_2^+ + e \rightarrow 1.08\ N(^2D) + 0.92\ N(^4S)$	$\left(1.8^{+0.4}_{-0.2}\right)[-7]$	(-0.39)	0	$T=T_e$; Notes h, i	Chp. 16 + Est.
b.		(2.7±0.3) [-7]	(-0.02)	0	$T=T_g$=200-480 K	Ref. 24-7 + Est.
4.	$NO_2^+ + e \rightarrow NO + O$	(3±2) [-7]	(-0.5±0.2)	0	$T=T_e$	Gst.
5.	$N_3^+ + e \rightarrow N + N_2$	(7±4) [-7]	(-1.0±0.5)	0		Est.
6.	$O_4^+ + e \rightarrow O + O + O_2$	(2.0±0.5) [-6]	(-1.0±0.5)	0	Probable Products	Chp. 16
7.	$NO^+ \cdot NO + e \rightarrow N + O + NO$	(1.7±0.5) [-6]	(-1.0±0.5)	0		
8.	$NO^+ \cdot N_2 + e \rightarrow N + O + N_2$	(1.5±0.5) [-6]	(-1.0±0.5)	0		Gst.
9.	$N_4^+ + e \rightarrow N_2 + N_2$	(2±1) [-6]	(-1.0±0.3)	0		Chp. 16
10.	$O_2^+ \cdot H_2O + e \rightarrow O_2 + H_2O$	(1.5±0.5) [-6]	(-0.2±0.2)	0		
11.	$NO^+ \cdot H_2O + e \rightarrow NO + H_2O$	(1.5±0.5) [-6]	(-0.2±0.2)	0		
12.	$NO^+ \cdot CO_2 + e \rightarrow NO + CO_2$	(1.5±0.5) [-6]	(-0.2±0.2)	0		
13.	$NO^+(H_2O)_2 + e \rightarrow NO + 2H_2O$	(2±1) [-6]	(-0.2±0.2)	0		
14.	$NO^+(H_2O)_3 + e \rightarrow NO + 3H_2O$	(3±1) [-6]	(-0.2±0.2)	0	Probable Products	Gst.
15.	$NO^+ \cdot H_2O \cdot N_2 + e \rightarrow NO + H_2O + N_2$	(2±1) [-6]	(-0.2±0.2)	0		
16.	$NO^+ \cdot H_2O \cdot CO_2 + e \rightarrow NO + H_2O + CO_2$	(2±1) [-6]	(-0.2±0.2)	0		
17.	$NO^+(H_2O)_2N_2 + e \rightarrow NO + 2H_2O + N_2$	(3±1) [-6]	(-0.2±0.2)	0		
18.	$NO^+(H_2O)_2CO_2 + e \rightarrow NO + 2H_2O + CO_2$	(3±1) [-6]	(-0.2±0.2)	0		

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
IV. Dissociative Recombination: (continued)						
19.	$NO_2^+ \cdot H_2O + e \rightarrow NO_2 + H_2O$	(1.5±0.5)[-6]	(-0.2±0.2)	0	Probable Products	Gst.
20.	$NO_2^+(H_2O)_2 + e \rightarrow NO_2 + 2H_2O$	(2±1)[-6]	(-0.2±0.2)	0		
21.a.	$H_3O^+ + e \rightarrow H_2O + H$	(1.3±0.3)[-6]	$\left(-1.0^{+0.1}_{-0.2}\right)$	0	300 K < T_e < 10,000K	Chp. 16 + Ref. 24-8
b.		(1.3±0.3)[-6]	$\left(-0.7^{+0.2}_{-0.3}\right)$	0	100 K < T_e < 300 K	
22.	$H_3O^+ \cdot N_2 + e \rightarrow H + H_2O + N_2$	(1.5±0.5)[-6]	(-0.2±0.2)	0	Probable Products	Gst.
23.	$H_3O^+ \cdot OH + e \rightarrow H_2O + H + OH$	(2±1)[-6]	$\left(-0.2^{+0.1}_{-0.3}\right)$	0		
24.	$H_3O^+ \cdot H_2O + e \rightarrow 2H_2O + H$	(2.8±0.4)[-6]	(-0.15±0.15)	0	Probable Products; Notes j, k	Chp. 16
25.	$H_3O^+(H_2O)_2 + e \rightarrow 3H_2O + H$	(5.1±0.7)[-6]	$\left(-0.05^{+0.05}_{-0.10}\right)$	0		
26.	$H_3O^+(H_2O)_3 + e \rightarrow 4H_2O + H$	(6.1±1.2)[-6]	(0.00±0.05)	0	Probable Products; Notes j, l	
27.	$H_3O^+(H_2O)_4 + e \rightarrow 5H_2O + H$	(7.4±1.5)[-6]	(0.0±0.2)	0	Probable Products; Note j	
28.	$H_3O^+(H_2O)_5 + e \rightarrow 6H_2O + H$	(9.3±2.0)[-6]	(0.0±0.2)	0	Probable Products; Notes j, m	
V. Mutual Neutralization:						
1.	$O^+ + O^- \rightarrow O + O$	(2.7±1.3)[-7]	(-0.5)	0		Chp. 16
2.	$N^+ + O^- \rightarrow N + O$	(2.6±0.8)[-7]	(-0.5)	0		
3.	$O_2^+ + O^- \rightarrow O_2 + O$	(1.0±0.3)[-7]	(-0.5)	0		Chp. 16 + Ref. 24-11

Table 24-1. (continued)

No.	Reaction	o	b	c	Notes	Sources
V. Mutual Neutrolizotion: (continued)						
4.	$O_2^+ + O_2^- \rightarrow O_2 + O_2$	(4.2±1.3)[-7]	(-0.5)	0		Chp. 16
5.	$O_2^+ + NO_2^- \rightarrow O_2 + NO_2$	(4.1±1.3)[-7]	(-0.5)	0		
6.	$O_2^+ + NO_3^- \rightarrow O_2 + NO_3$	(1.3±0.5)[-7]	(-0.5)	0		
7.	$NO^+ + O^- \rightarrow NO + O$	(4.9±1.5)[-7]	(-0.5)	0		
8.	$NO^+ + O_2^- \rightarrow NO + O_2$	(6±1)[-7]	(-0.5)	0		Ref. 24-11
9.	$NO^+ + NO_2^- \rightarrow NO + NO_2$	$\left(1.0^{+0.8}_{-0.4}\right)$[-7]	(-0.5)	0	Note n	Chp. 16 + Refs. 24-15, 24-16
10.	$NO^+ + NO_3^- \rightarrow NO + NO_3$	$\left(9^{+9}_{-5}\right)$[-8]	(-0.5)	0		
11.	$N_2^+ + O_2^- \rightarrow N_2 + O_2$	(1.6±0.5)[-7]	(-0.5)	0		Chp. 16
12.	$X^+ + Y^- \rightarrow$ Products (probably X+Y)	$\left(1.0^{+4.0}_{-0.6}\right)$[-7]	(-0.5)	0	Note o	Est.
VI. Three-Body Ion-Ion Recombination:						
1.	$X^+ + Y^- + M \rightarrow$ Products	(3±1)[-25]	(-2.5)	0	Note p	Chp. 16
2.	X^+(cluster) + Y^- + M → Products	(1)[-25.0±0.2]	(-2.5)	0	Note q	Gst.
3.	$X^+ + Y^-$(cluster) + M → Products	(1)[-25.0±0.2]	(-2.5)	0		
4.	X^+(cluster) + Y^-(cluster) + M → Products	(1)[-25.0±0.2]	(-2.5)	0		
VII. Radiative Attachment:						
1.	$O + e \rightarrow O^- + h\nu$	(1.3±0.1)[-15]	0	0		Chp. 17

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
VII. Radiative Attachment: (continued)						
2.	$O_2 + e \rightarrow O_2^- + h\nu$	(2)[-19±1]	0	0		Chp. 17
3.	$OH + e \rightarrow OH^- + h\nu$	(2.5±1.5)[-15]	(-0.25)	0	Note r	Ref. 24-17
4.	$O_3 + e \rightarrow O_3^- + h\nu$	(1)[-17±3]	0	0	Slow compared with reactions XI.2(a,b)	Est.
5.	$NO_2 + e \rightarrow NO_2^- + h\nu$	(1)[-17±2]	0	0	See Reaction IX.7	Est.
VIII. Photodetachment: (See Note s)						
1.a.	$O^- + h\nu \rightarrow O + e$	(1.4±0.1)[0]	0	0		Chp. 17; Ref. 24-18
b.	$\rightarrow O(^1D) + e$	(7.6)[-2.0±0.2]	0	0	Note t	Ref. 24-19
2.	$O_2^- + h\nu \rightarrow O_2 + e$	(0.33±0.10)[0]	0	0		Chp. 17; Ref. 24-18
3.	$OH^- + h\nu \rightarrow OH + e$	(1)[0±1]	0	0		Chp. 17
4.	$O_3^- + h\nu \rightarrow O_3 + e$	(8±2)[-2]	0	0	Note u	Ref. 24-20
5.	$NO_2^- + h\nu \rightarrow NO_2 + e$	(5±3)[-2]	0	0	Est. (J.R. Peterson) from data of Ref. 24-21	
6.	$O_4^- + h\nu \rightarrow 2O_2 + e$	$\left(3^{+3}_{-2}\right)$[-1]	0	0	See Reaction XXII.2; Probable Products	Ref. 24-18
7.	$NO_3^- + h\nu \rightarrow NO_3 + e$	(5)[-3±2]	0	0	Probable Products	Ref. 24-22
8.	$CO_4^- + h\nu \rightarrow CO_2 + O_2 + e$	(3)[-2±1]	0	0	Probable Products	Ref. 24-20

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
IX. Three-Body Attachment:						
1.	$O_2 + e + O \rightarrow O_2^- + O$	(1)[-31±2]	0	0	Note v	Est.
2.	$O_2 + e + O_2 \rightarrow O_2^- + O_2$	(1.4±0.2)[-29]	(-1)	600	T = 195-600 K; k_{300} = (1.9±0.3)[-30]	Chp. 17
3.	$O_2 + e + N_2 \rightarrow O_2^- + N_2$	(1.0±0.5)[-31]	0	0		Chp. 17
4.	$O_2 + e + H_2O \rightarrow O_2^- + H_2O$	(1.4±0.2)[-29]	0	0	T = 300-400 K	Chp. 17
5.	$O_2 + e + CO_2 \rightarrow O_2^- + CO_2$	(3.3±0.7)[-30]	0	0	T = 300-525 K	Chp. 17
6.	$NO + e + M \rightarrow$ Products	(8)[-31]	0	0	M = NO	Chp. 17
7.	$NO_2 + e\ (+M) \rightarrow NO_2^-\ (+M)$	(4)[-11]	0	0	Note w; See Reaction VII.5	Chp. 17
X. Collisional Detachment:						
1.	$O^- + O_2 \rightarrow O + e + O_2$	(2.3±1.0)[-9]	0	26,000±3000	T_i < 20,000 K; k'_{3000} = (4)[-13] ± 1[-]	Chp. 17
2.	$O^- + N_2 \rightarrow O + e + N_2$	(2.3)[-9.0±0.5]	0	26,000±3000		Chp. 17
3.	$O_2^- + O \rightarrow O_2 + e + O$	(3.6)[-11]	0	5000	Note r; k_{300} (2.1)[-18]	Ref. 24-23
4.	$O_2^- + O_2 \rightarrow O_2 + e + O_2$	(2.7±0.3)[-10]	(0.5)	5590	T = 375-600 K; k_{300} = (2.2 ± 0.3)[-18]	Chp. 17
5.	$O_2^- + O_2(a^1\Delta_g) \rightarrow O_2 + e + O_2$	$\left(2^{+2}_{-1}\right)$[-10]	-	-		Chps. 17, 20
6.	$O_2^- + N_2 \rightarrow O_2 + e + N_2$	(1.9±0.4)[-12]	(1.5)	4990	T = 375-600K; k_{300} = (1.1 ± 0.3)[-19]	Chp. 17

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
X. Collisional Detachment: (continued)						
7.	$O_2^- + H_2O \rightarrow O_2 + e + H_2O$	(5.0)[-9]	0	5000	Note r; $k_{300} = (2.9)[-16]$	Ref. 24-23
8.	$O_2^- + CO_2 \rightarrow O_2 + e + CO_2$	(1.2)[-9]	0	5000	Note r; $k_{300} = (6.9)[-17]$	
XI. Dissociative Attachment:						
1.	$O_2 + e \rightarrow O^- + O$	-	-	-	$k \sim (1)[-16]$ for $T > 2000$ K; Endothermic $c > (4)[4]$ at $T < 300$ K; Strong T_v dependence at high T_e.	Chps. 17, 20
2. a.	$O_3 + e \rightarrow O^- + O_2$	(9±2)[-12]	(1.5)	0	T = 200-300 K; See Reaction VII. 4	Chp. 17
b.	$\rightarrow O_2^- + O$	(5.4)[-10.0±0.3]	(1.5)	13,200	$T = T_e$; No dependence on T for T < 360 K; $T_{ref} = 3000$ K; $k_{3000} = (6.6)[-12.0\pm0.3]$	Est. based on Ref. 24-24
3.	$HNO_3 + e \rightarrow NO_2^- + OH$	(5±3)[-8]	-	-		Ref. 24-25
XII. Associative Detachment:						
1.	$O^- + O \rightarrow O_2 + e$	(2)[-10.0±0.3]	-	-		Ref. 24-26
2.	$O^- + N \rightarrow NO + e$	$\left(2\,^{+2}_{-1}\right)[-10]$	-	-		
3.	$O^- + O_2 \rightarrow O_3 + e$	-	-	-	$k < (5)[-15]$ at T = 300 K and T_i = 300-10,000 K; Endothermic $c \sim (5)[3]$	Chp. 17

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XII. Associative Detachment: (continued)						
4.	$O^- + O_2(a^1\Delta_g) \rightarrow O_3 + e$	(3)[-10.0±0.3]	-	-	Cf. Reaction XV.1	Chps. 17, 20
5.	$O^- + NO \rightarrow NO_2 + e$	(2.5±0.6)[-10]	(-0.8)	0	T_i = 300-2000 K; Cf. Reaction XXIII.2	Ref. 24-27
6.	$O^- + N_2 \rightarrow N_2O + e$	-	-	-	k < (1)[-14] at T_i=300K; Note x	Ref. 24-28
7.	$O^- + H_2 \rightarrow H_2O + e$	(6.0±1.0)[-10]	(-0.2)	0	T = T_i < 3000 K	Ref. 24-27
8.	$O^- + CO \rightarrow CO_2 + e$	(6±1)[-10]	(-0.32)	0		
9.	$O^- + O_3 \rightarrow 2O_2 + e$	-	-	-	Slow compared with Reaction XV.3	Est.
10.	$O_2^- + O \rightarrow O_3 + e$	(1.5)[-10.0±0.3]	-	-	See Reaction XV.7	Ref. 24-26
11.	$O_2^- + N \rightarrow NO_2 + e$	(3)[-10.0±0.3]	-	-		
12.	$OH^- + O \rightarrow HO_2 + e$	(2)[-10.0±0.3]	-	-		Ref. 24-29
13.	$OH^- + H \rightarrow H_2O + e$	(1.4)[-9.0±0.3]	-	-		Ref. 24-30
14.	$O_3^- + O \rightarrow 2O_2 + e$	(1)$\left[-11\ ^{+1}_{-2}\right]$	-	-	Note v	Est.
15.	$NO_2^- + H \rightarrow HNO_2 + e$	-	-	-	k < (8)[-11]	Ref. 24-31
16.	$NO_3^- + H \rightarrow HNO_3 + e$	-	-	-	k < (5)[-11]	
17.	$CO_3^- + O \rightarrow CO_2 + O_2 + e$	-	-	-	Slow compared to Reaction XVI.42	Ref. 24-26

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIII.	Positive-Ion Charge Transfer:					
1.	$O^+ + H \rightarrow O + H^+$	(6.8±3.0)[-10]	0	0		Chp. 18A
2.a.	$O^+ + O_2 \rightarrow O + O_2^+$	(2.0±0.2)[-11]	(-0.40±0.14)	0	$T = T_i \leq 1800$ K	Ref. 24-27
b.		(1.3±0.2)[-12]	(1.20±0.13)	0	$T = T_i > 1800$ K	
3.	$O^+(^2D) + O_2 \rightarrow O + O_2^+(a^4\Pi_u), (A^3\Sigma_u^+)$	$(3)\left[-10.0^{+0.5}_{-1.0}\right]$	0	0		Chp. 20
4.a.	$O^+ + NO \rightarrow O + NO^+$ (see Note y)	(8.0±1.2)[-13]	(-0.21)	0	$T = T_i \leq 1000$ K; $T_v = 300$ K	Ref. 24-32
b.		(7±1)[-14]	(1.66)	0	$T = T_i > 1000$ K; $T_v = 300$ K	
5.	$O^+(^2D) + N_2 \rightarrow O + N_2^+$	(3)[-10±1]	0	0		Chp. 20
6.	$O^+ + NO_2 \rightarrow O + NO_2^+$	(1.6±0.3)[-9]	0	0	Data at 393 K	Chp. 18A
7.	$O^+ + N_2O \rightarrow O + N_2O^+$	(2.2±1.0)[-10]	0	0	Cf. Reaction XIV.4	
8.	$O^+ + H_2O \rightarrow O + H_2O^+$	(2.3±0.3)[-9]	0	0		
9.	$N^+ + O \rightarrow N + O^+$	(1)[-12]	-	-		Est.
10.a.	$N^+ + O_2 \rightarrow N + O_2^+$ (see Notes z, aa)	(2.8±1.0)[-10]	$\left(0.00^{+0.80}_{-0.17}\right)$	0	$T = T_i < 4600$ K	Ref. 24-27
b.		(6±1)[-11]	(0.57±0.05)	0	$T = T_i > 4600$ K	
11.	$N^+ + NO \rightarrow N + NO^+$	(8.0±2.4)[-10]	-	-		Chp. 18A
12.	$N^+ + CO \rightarrow N + CO^+$	(9±3)[-10]	-	-		Ref. 24-34
13.	$N^+ + H_2O \rightarrow N + H_2O^+$	(2.6±0.4)[-9]	-	-		Chp. 18A

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIII.	Positive-Ion Charge Transfer: (continued)					
14.	$N^+ + CO_2 \rightarrow N + CO_2^+$	(1.3±0.4)[-9]	-	-		Ref. 24-34
15.	$H^+ + O \rightarrow H + O^+$	(3.8±2.0)[-10]	-	-		Chp. 18A
16.	$H^+ + NO \rightarrow H + NO^+$	(1.9±0.5)[-9]	-	-		Chp. 18A
17.	$O_2^+(a^4\Pi_u) + O \rightarrow O_2 + O^+$	(5)[-10.0±0.3]	-	-		Gst.
18.	$O_2^+ + Na \rightarrow O_2 + Na^+$	(6.7)[-10±1]	0	0	Cf. Reaction XIV.16	Chp. 18A
19.	$O_2^+(a^4\Pi_u) + O_2 \rightarrow O_2 + O_2^+$				See Note ab	
20.	$O_2^+ + NO \rightarrow O_2 + NO^+$	(4.5±1.0)[-10]	0	0	300 K < T < 900 K	Chp. 18A + Ref. 24-35
21.	$O_2^+(a^4\Pi_u) + NO \rightarrow O_2 + NO^+$	(1.1±0.3)[-9]	0	0	$T = T_i < 2000$ K	Ref. 24-35
22.	$O_2^+(a^4\Pi_u) + N_2 \rightarrow O_2 + N_2^+$	(4.1±1.6)[-10]	0	0		Ref. 24-36
23.	$O_2^+ + NO_2 \rightarrow O_2 + NO_2^+$	(6.6±2.0)[-10]	-	-		Chp. 18A
24.	$O_2^+ + H_2O_2 \rightarrow O_2 + H_2O_2^+$	(1.5±0.4)[-9]	0	0	$T = T_i$ < 700 K	Ref. 24-37
25.	$NO^+ + Na \rightarrow NO + Na^+$	(7.0±3.0)[-11]	0	0		Chp. 18A
26.	$OH^+ + O_2 \rightarrow OH + O_2^+$	(2.0±0.5)[-10]	-	-		Chp. 18A
27.	$CO^+ + O \rightarrow CO + O^+$	(1.4±0.8)[-10]	-	-		Chp. 18A
28.	$CO^+ + NO \rightarrow CO + NO^+$	(3.3±1.0)[-10]	-	-		Chp. 18A

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIII.	Positive-Ion Charge Transfer: (continued)					
29.a	$N_2^+ + O \rightarrow N_2 + O^+$ (Cf. Reaction XIV. 19)	(1.0±0.5)[-11]	(-0.23)	0	$T < T_i < 1500$ K	Ref. 24-38
b		(3.6±1.4)[-12]	(0.41)	0	$T = T_i > 1500$ K	
30.	$N_2^+ + N \rightarrow N_2 + N^+$	-	-	-	k = (1)[-11]	Chp. 18A
31.	$N_2^+ + Na \rightarrow N_2 + Na^+$	(5.8±3.0)[-10]	0	0		
32.a	$N_2^+ + O_2 \rightarrow N_2 + O_2^+$ (Cf. Reaction XIV. 20)	(5.0±1.0)[-11]	(-0.8±0.2)	0	$T < T_i < 3560$ K	Chp. 18A + Ref. 24-27
b		(2.5±0.5)[-12]	(1.4±0.3)	0	$T = T_i > 3560$ K	
33.	$N_2^+ + NO \rightarrow N_2 + NO^+$	(3.3±1.5)[-10]	-	-	Note ac	Chp. 18A
34.	$N_2^+ + H_2O \rightarrow N_2 + H_2O^+$	-	-	-	Note ad	
35.	$N_2^+ + CO_2 \rightarrow N_2 + CO_2^+$	(9±3)[-10]	-	-		Ref. 24-34
36.	$NO_2^+ + NO \rightarrow NO_2 + NO^+$	(2.9±1.0)[-10]	-	-		Chp. 18A
37.	$H_2O^+ + O_2 \rightarrow H_2O + O_2^+$	(2.0±0.5)[-10]	-	-		
38.	$CO_2^+ + O \rightarrow CO_2 + O^+$	(1.0±0.6)[-10]	-	-	Cf. Reaction XIV. 27	
39.	$CO_2^+ + O_2 \rightarrow CO_2 + O_2^+$	(5±2)[-11]	-	-		
40.	$CO_2^+ + NO \rightarrow CO_2 + NO^+$	(1.2±0.4)[-10]	-	-		

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIII.	Positive-Ion Charge Transfer: (continued)					
41.	$O_4^+ + O_2(a^1\Delta_g) \rightarrow 2O_2 + O_2^+$	(1) [-10]	-	-		Gst.
42.	$O_4^+ + NO \rightarrow 2O_2 + NO^+$	(5) [-10]	-	-		Est.
43.	$O_4^+ + NO_2 \rightarrow 2O_2 + NO_2^+$	(5) [-10]	-	-		
44.	$N_4^+ + O_2 \rightarrow 2N_2 + O_2^+$	(4±1)[-10]	-	-	Data at 200 K	Chp. 18A
45.	$H_2O_2^+ + NO \rightarrow H_2O_2 + NO^+$	(5.0±1.5)[-10]	0	0	$T = T_i < 700$ K	Ref. 24-37
46.	$O_2^+ \cdot H_2O + O_2(a^1\Delta_g) \rightarrow O_2 + H_2O + O_2^+$	(1) [-10]	-	-		Gst.
47.	$O_2^+ \cdot H_2O + NO \rightarrow O_2 + H_2O + NO^+$	(1) [-10]	-	-		
48.	$O_2^+ \cdot H_2O + NO_2 \rightarrow O_2 + H_2O + NO_2^+$	(1) [-10]	-	-		
XIV.	Positive-Ion-Atom Interchange:					
1.	$O^+ + NO \rightarrow O_2^+ + N$	-	-	-	k < (1)[-12]; See Reaction XIII.4	Est.
2.a.	$O^+ + N_2 \rightarrow NO^+ + N$ (See Note ae)	(1.2±0.1)[-12]	(-1.0±0.4)	0	T < 750 K	Chp. 18A + Ref. 24-27
b.		(8.0±2.0)[-14]	(2.0±0.2)	0	T > 750 K	
3.	$O^+ + H_2 \rightarrow OH^+ + H$	(2.0±0.5)[-9]	-	-		Chp. 18A
4.	$O^+ + N_2O \rightarrow NO^+ + NO$	(2.3±1.0)[-10]	-	-	See Reaction XIII.7	
5.	$O^+ + CO_2 \rightarrow O_2^+ + CO$	(1.1±0.3)[-9]	0	0		

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIV.	Positive-Ion-Atom Interchange: (continued)					
6.a.	$N^+ + O_2 \rightarrow NO^+ + O$ (See Note z)	$(2.8 \pm 1.0)[-10]$	$\left(0.00^{+0.80}_{-0.17}\right)$	0	$T = T_i \approx 4600$ K	Chp. 18A
b.		$(6 \pm 1)[-11]$	(0.57 ± 0.05)	0	$T = T_i \approx 4600$ K	
7.	$N^+ + H_2 \rightarrow NH^+ + H$	$(5.6 \pm 2.0)[-10]$	0	0		
8.	$C^+ + O_2 \rightarrow CO^+ + O$	$(1.1 \pm 0.3)[-9]$	0	0		Ref. 24-41
9.	$C^+ + CO_2 \rightarrow CO^+ + CO$	$(1.8 \pm 0.6)[-9]$	0	0		
10.	$Fe^+ + O_3 \rightarrow FeO^+ + O_2$	$(1.5 \pm 0.8)[-10]$	0	0		Chp. 18A
11.	$S^+ + O_2 \rightarrow SO^+ + O$	$(1.6 \pm 0.3)[-11]$	0	0		
12.	$U^+ + O_2 \rightarrow UO^+ + O$	$\left(8.5^{+4.0}_{-1.0}\right)[-10]$	0	0		
13.	$U^+ + NO \rightarrow UO^+ + N$	$(1)\left[-9^{+0}_{-1}\right]$	0	0		Est.
14.	$U^+ + N_2 \rightarrow UN^+ + N$	-	-	-	$k < (1)[-11]$; see Note af	Chp. 18A
15.a.	$O_2^+ + N \rightarrow NO^+ + O$	$(1.2 \pm 0.4)[-10]$	0	0		Chp. 18A + Ref. 24-42
b.	$\rightarrow O^+ + NO$	-	-	-	Note ag	Chp. 18A
16.	$O_2^+ + Na \rightarrow NaO^+ + O$	$(7.7 \pm 3.0)[-11]$	0	0	Cf. Reaction XIII. 18	
17.	$O_2^+ + N_2 \rightarrow NO^+ + NO$	$(1)\left[-16^{+1}_{-3}\right]$	0	0	Note ah	Est.
18.	$O_2^+ + H_2 \rightarrow$ Products	-	-	-	$k < (1)[-11]$	Chp. 18A

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIV.	Positive-Ion-Atom Interchange: (continued)					
19.a.	$N_2^+ + O \rightarrow NO^+ + N$ (Cf. Reaction XIII.29)	(1.3±0.7)[-10]	(-0.46)	0	$T = T_i < 1500$ K	Chp. 18A + Ref. 24-38
b.		(4.8±2.0)[-11]	(0.18)	0	$T = T_i > 1500$ K; See Note aj	Chp. 18A
20.	$N_2^+ + O_2 \rightarrow NO^+ + NO$	(1) [-17±2]	0	0	Cf. Reaction XIII.32	Est.
21.	$N_2^+ + H_2 \rightarrow N_2H^+ + H$	(1.7±0.3)[-9]	0	0		Chp. 18A
22.	$N_2^+ + H_2O \rightarrow N_2H^+ + OH$	-	-	-	Note ad	
23.	$NO_2^+ + O \rightarrow NO^+ + O_2$	-	-	-	$k < 1[-11]$	Ref. 24-42
24.	$N_3^+ + O_2 \rightarrow \begin{cases} NO^+ + N_2 + O \\ NO_2^+ + N_2 \end{cases}$	(6.0±1.8)[-11]	(-0.52)	0	$T = T_i < 900$ K; Note aj	Ref. 24-43
25.	$N_3^+ + NO \rightarrow \begin{cases} NO^+ + N_2 + N \\ N_2O^+ + N_2 \end{cases}$	(1.4±0.4)[-10]	(-0.38)	0	$T = T_i < 600$ K; Note aj	
26.	$H_2O^+ + H_2O \rightarrow H_3O^+ + OH$	(1.8±0.3)[-9]	0	0		Chp. 18A
27.	$CO_2^+ + O \rightarrow O_2^+ + CO$	(1.6±0.8)[-10]	0	0	Cf. Reaction XIII.38	
28.	$O_4^+ + O \rightarrow O_2^+ + O_3$	(3±2) [-10]	-	-		
29.	$O_4^+ + H_2O \rightarrow O_2^+ \cdot H_2O + O_2$	(1.5±0.5)[-9]	-	-		
30.	$O_2^+ \cdot N_2 + O_2 \rightarrow O_4^+ + N_2$	(1.0±0.5)[-9]	-	-		Est.

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIV.	Positive-Ion-Atom Interchange: (continued)					
31.	$O_2^+ \cdot N_2 + H_2O \rightarrow O_2^+ \cdot H_2O + N_2$	(4±2)[-9]	-	-		Chp. 18A
32.	$NO^+ \cdot NO + H_2O \rightarrow NO^+ \cdot H_2O + NO$	(1.4±0.3)[-9]	-	-		Chp. 18A
33.	$H_2O_2^+ + H_2O \rightarrow H_3O^+ + HO_2$	(1.7±0.5)[-9]	0	0	$T = T_i < 700$ K	Ref. 24-37
34.	$H_3O^+ + HNO_3 \rightarrow NO_2^+ \cdot H_2O + H_2O$	(1.6±0.6)[-9]	0	0		Ref. 24-25
35.	$O_2^+ \cdot H_2O + O_2 \rightarrow O_4^+ + H_2O$	(2)[-10]	0	2300	$k_{300} = (9.4)[-14]$	Est.
36. a.	$O_2^+ \cdot H_2O + H_2O \rightarrow H_3O^+ + OH + O_2$	(2.0±1.0)[-10]	-	-		Chp. 18A
b.	$\rightarrow H_3O^+ \cdot OH + O_2$	(1.0±0.4)[-9]	-	-		Chp. 18A
37.	$NO^+ \cdot N_2 + H_2O \rightarrow NO^+ \cdot H_2O + N_2$	(1.0)[-9]	-	-		Gst.
38.	$NO^+ \cdot N_2 + CO_2 \rightarrow NO^+ \cdot CO_2 + N_2$	(1.0)[-9]	-	-		Gst.
39.	$NO^+ \cdot H_2O + O \rightarrow NO_2^+ + H_2O$	-	-	-	$k < (1)[-11]$	Ref. 24-42
40.	$NO^+ \cdot H_2O + H \rightarrow H_3O^+ + NO$	-	-	-	$k < (7)[-12]$	Ref. 24-28
41.	$NO^+ \cdot H_2O + NO \rightarrow NO^+ \cdot NO + H_2O$	(2.0±0.4)[-10]	0	2300	$k_{300} = (9.4 \pm 1.9)[-14]$	Ref. 24-44
42.	$NO^+ \cdot H_2O + OH \rightarrow H_3O^+ + NO_2$	-	-	-	$k \leq (6.0)[-11]$	Ref. 24-45
43.	$NO^+ \cdot H_2O + HO_2 \rightarrow H_3O^+ + NO + O_2$	(5.0)[-10]	-	-		Est.

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIV.	Positive-Ion-Atom Interchange: (continued)					
44.a.	$NO^+ \cdot H_2O + H_2O_2 \rightarrow H_3O^+ + NO_2 + OH$	(3.0)[-11]	-	-	Note ak	Ref. 24-28
b.	$\rightarrow NO_2^+ + 2H_2O$	(3.0)[-11]	-	-		
c.	$\rightarrow NO_2^+ \cdot H_2O + H_2O$	(3.0)[-11]	-	-		
45.	$NO^+ \cdot CO_2 + NO \rightarrow NO^+ \cdot NO + CO_2$	(1.0)[-9]	-	-		Gst.
46.	$NO^+ \cdot CO_2 + H_2O \rightarrow NO^+ \cdot H_2O + CO_2$	(1.0±0.3)[-9]	-	-		Chp. 18A
47.	$NO^+(H_2O)_3 + H_2O \rightarrow H_3O^+(H_2O)_2 \cdot HNO_2$	(7±2)[-11]	-	-		
48.	$NO^+ \cdot H_2O \cdot N_2 + CO_2 \rightarrow NO^+ \cdot H_2O \cdot CO_2 + N_2$	(1.0)[-9]	-	-		Est.
49.	$NO^+ \cdot H_2O \cdot CO_2 + H_2O \rightarrow NO^+(H_2O)_2 + CO_2$	(1.0)[-9]	-	-		
50.	$NO^+(H_2O)_2N_2 + CO_2 \rightarrow NO^+(H_2O)_2CO_2 + N_2$	(1.0)[-9]	-	-		
51.	$NO^+(H_2O)_2CO_2 + H_2O \rightarrow NO^+(H_2O)_3 + CO_2$	(1.0)[-9]	-	-		
52.	$NO_2^+ \cdot H_2O + NO \rightarrow NO^+ \cdot H_2O + NO_2$	(3.1±0.9)[-11]	0	0		Ref. 24-25

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIV.	Positive-Ion-Atom Interchange: (continued)					
53.	$NO_2^+(H_2O)_2 + H_2O \rightarrow H_3O^+ \cdot H_2O + HNO_3$	-	-	-	k = (1.0)[-10]	Ref. 24-25
54.	$H_3O^+ \cdot N_2 + H_2O \rightarrow H_3O^+ \cdot H_2O + N_2$	(1.0)[-9]	-	-		Est.
55.	$H_3O^+ \cdot OH + H_2O \rightarrow H_3O^+ \cdot H_2O + OH$	(1.4±0.5)[-9]	0	0		Chp. 18A
XV.	Negative-Ion Charge Transfer:					
1.	$O^- + O_2(a^1\Delta_g) \rightarrow O + O_2^-$	-	-	-	k_{300} = (1)[-10]; Cf. Reaction XII.4	Est.
2.	$O^- + OH \rightarrow O + OH^-$	(5.0)[-10]	-	-		Gst.
3.	$O^- + O_3 \rightarrow O + O_3^-$	(5.3±2.0)[-10]	0	0	See Reaction XII.9	Chp. 18A
4.	$O^- + NO_2 \rightarrow O + NO_2^-$	(1.2±0.4)[-9]	-	-		Chp. 18A
5.	$O^- + NO_3 \rightarrow O + NO_3^-$	(5.0)[-10]	-	-		Gst.
6.	$H^- + NO_2 \rightarrow H + NO_2^-$	(2.9±1.0)[-9]	0	0		Chp. 18A
7.	$O_2^- + O \rightarrow O_2 + O^-$	(1.5)[-10.0±0.3]	-	-	See Reaction XII.10	Ref. 24-26
8.	$O_2^- + OH \rightarrow O_2 + OH^-$	(5)[-10]	-	-		Est.
9.	$O_2^- + O_3 \rightarrow O_2 + O_3^-$	(4.0±1.3)[-10]	0	0		Chp. 18A
10.	$O_2^- + NO_2 \rightarrow O_2 + NO_2^-$	(1.2±0.5)[-9]	0	0		Chp. 18A + Ref. 24-46

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XV.	Negative-Ion Charge Transfer: (continued)					
11.	$O_2^- + NO_3 \rightarrow O_2 + NO_3^-$	(5)[-10]	-	-		Est.
12.	$NO^- + O_2 \rightarrow NO + O_2^-$	(5±2)[-10]	0	0		Chp. 18A
13.	$OH^- + O_3 \rightarrow OH + O_3^-$	(5)[-10]	-	-		Est.
14.	$OH^- + NO_2 \rightarrow OH + NO_2^-$	(1.0±0.3)[-9]	0	0		Chp. 18A
15.	$OH^- + NO_3 \rightarrow OH + NO_3^-$	(1)[-9]	-	-		Est.
16.	$O_3^- + NO_2 \rightarrow O_3 + NO_2^-$	(2.8±1.0)[-10]	0	0	$T = T_i < 2000$ K; See Note a[ℓ]	Ref. 24-47
17.	$O_3^- + NO_3 \rightarrow O_3 + NO_3^-$	(5)[-10]	-	-		Est.
18.	$NO_2^- + NO_3 \rightarrow NO_2 + NO_3^-$	(5)[-10]	-	-		
19.	$O_4^- + OH \rightarrow 2O_2 + OH^-$	(5)[-10]	-	-		
20.	$O_4^- + O_3 \rightarrow 2O_2 + O_3^-$	(3)[-10]	-	-		
21.	$O_4^- + NO_2 \rightarrow 2O_2 + NO_2^-$	(5)[-10]	-	-		
22.	$O_4^- + NO_3 \rightarrow 2O_2 + NO_3^-$	(5)[-10]	-	-		
23.	$OONO^- + NO_3 \rightarrow NO + O_2 + NO_3^-$	(5)[-10]	-	-		
24.	$CO_3^- + NO_3 \rightarrow CO_2 + O + NO_3^-$	(5)[-10]	-	-		

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XV.	Negative-Ion Charge Transfer: (continued)					
25.	$CO_4^- + OH \rightarrow CO_2 + O_2 + OH^-$	(5)[-10]	-	-		Est.
26.	$CO_4^- + O_3 \rightarrow CO_2 + O_2 + O_3^-$	(1.3)[-10.0±0.3]	-	-		Ref. 24-46
27.	$CO_4^- + NO_3 \rightarrow CO_2 + O_2 + NO_3^-$	(5)[-10]	-	-		Est.
28.	$O_2^- \cdot H_2O + O_3 \rightarrow O_2 + H_2O + O_3^-$	(2.3)[-10.0±0.3]	-	-	Note am	Chp. 18A + Ref. 24-46
29.	$O_2^-(H_2O)_2 + O_3 \rightarrow O_2 + 2H_2O + O_3^-$	(3.4±1.0)[-10]	0	0		Chp. 18A
XVI.	Negative-Ion-Atom Interchange:					
1.	$O^- + N_2O \rightarrow NO^- + NO$	(2.3±0.5)[-10]	(-0.23)	-	$T = T_i + 2000$ K	Ref. 24-48
2.	$O^- + HNO_2 \rightarrow NO_2^- + OH$	(1)[-9]	-	-		Est.
3.	$O^- + HNO_3 \rightarrow NO_3^- + OH$	(3.0±1.2)[-9]	-	-		Ref. 24-25
4.	$O^- + CH_4 \rightarrow OH^- + CH_3$	(8±2)[-11]	(-0.12)	-	$T = T_i + 600$ K	Ref. 24-48
5.	$O_2^- + N \rightarrow O^- + NO$	(1)[-10.0±0.3]	-	-		Ref. 24-48
6.	$O_2^- + N_2O \rightarrow O_3^- + N_2$	-	-	-	k (2)[-14]	Ref. 24-49
7.	$O_2^- + HNO_2 \rightarrow NO_2^- + HO_2$	(1)[-9]	-	-		Est.
8.	$O_2^- + HNO_3 \rightarrow NO_3^- + HO_2$	(2.8±1.2)[-9]	-	-		Ref. 24-25
9.	$OH^- + HNO_2 \rightarrow NO_2^- + H_2O$	(1)[-9]	-	-		Est.

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XVI.	Negative-Ion-Atom Interchange: (continued)					
10.	$OH^- + HNO_3 \rightarrow NO_3^- + H_2O$	(1)[-9]	-	-		Est.
11.	$O_3^- + O \rightarrow O_2^- + O_2$	(3.2)[-10.0±0.3]	-	-		Ref. 24-26
12.	$O_3^- + H \rightarrow OH^- + O_2$	(8.4)[-10.0±0.3]	-	-		Ref. 24-31
13.	$O_3^- + NO \rightarrow NO_2^- + O_2$	(2.8±0.8)[-12]	(-1.8)	0	$T = T_i$ 600 K; Note an	Ref. 24-47
14.	$O_3^- + N_2 \rightarrow N_2O^- + O_2$	-	-	-	k < (1)[-15]	Chp. 18A
15.	$O_3^- + NO_2 \rightarrow NO_3^- + O_2$	-	-	-	Note ao	
16.	$O_3^- + N_2O \rightarrow O_4^- + N_2$	-	-	-	k < (2)[-14]	Ref. 24-49
17.	$O_3^- + CO_2 \rightarrow CO_3^- + O_2$	(5.5±1.7)[-10]	(-0.49)	0	$T = T_i$ < 600 K; Note ao	Ref. 24-47
18.	$O_3^- + HNO_2 \rightarrow NO_2^- + OH + O_2$	(1)[-9]	-	-		Est.
19.	$O_3^- + HNO_3 \rightarrow NO_3^- + OH + O_2$	(1)[-9]	-	-		Est.
20.	$NO_2^- + O \rightarrow$ Products	-	-	-	k < (1)[-11]	Chp. 18A
21.	$NO_2^- + N \rightarrow$ Products	-	-	-	k < (1)[-11]	Chp. 18A
22.	$NO_2^- + H \rightarrow OH^- + NO$	(3.7)[-10.0±0.3]	-	-		Ref. 24-31
23.	$NO_2^- + O_3 \rightarrow NO_3^- + O_2$	(1.8±0.6)[-11]	-	-		Chp. 18A
24.	$NO_2^- + NO_2 \rightarrow NO_3^- + NO$	-	-	-	k ≤ (2.0)[-13]; Note ap	Chp. 18A + Ref. 24-25

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XVI.	Negative-Ion-Atom Interchange: (continued)					
25.	$NO_2^- + N_2O \rightarrow NO_3^- + N_2$	-	-	-	k (1)[-12]	Ref. 24-49
26.	$NO_2^- + HNO_3 \rightarrow NO_3^- + HNO_2$	(1.6±0.6)[-9]	-	-		Ref. 24-25
27.	$O_4^- + O \rightarrow O_3^- + O_2$	(4±2)[-10]	-	-	Note aq	Chp. 18A
28.	$O_4^- + NO \rightarrow OONO^- + O_2$	(2.5±0.8)[-10]	-	-		
29.	$O_4^- + H_2O \rightarrow O_2^- \cdot H_2O + O_2$	(1.4±0.4)[-9]	-	-		
30.	$O_4^- + CO_2 \rightarrow CO_4^- + O_2$	(4.3±1.3)[-10]	-	-		
31.	$O_4^- + HNO_2 \rightarrow NO_2^- + HO_2 + O_2$	(1)[-9]	-	-		Est.
32.	$O_4^- + HNO_3 \rightarrow NO_3^- + HO_2 + O_2$	(1)[-9]	-	-		
33.	$NO_3^- + O \rightarrow$ Products	-	-	-	k < (1)[-11]	Chp. 18A
34.	$NO_3^- + N \rightarrow NO_2^- + NO$	-	-	-		
35.	$NO_3^- + H \rightarrow NO_2^- + OH$	-	-	-	k (5)[-10]	Ref. 24-31
36.	$NO_3^- + NO \rightarrow NO_2^- + NO_2$	-	-	-	k < (1)[-12]; Note ap	Chp. 18A
37.	$NO_3^- + O_3 \rightarrow NO_2^- + 2O_2$	-	-	-	k < (1)[-13]	Ref. 24-28
38.	$OONO^- + H \rightarrow \left\{ \begin{matrix} NO_2^- + OH \\ OH^- + NO_2 \end{matrix} \right\}$	(7.2)[-10.0±0.3]	-	-		Ref. 24-31

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XVI.	Negative-Ion-Atom Interchange: (continued)					
39.	$OONO^- + NO \rightarrow NO_2^- + NO_2$	(1.5)[-11±1]	-	-	Note ap	Chp. 18A
40.	$OONO^- + HNO_2 \rightarrow NO_2^- + NO + HO_2$	(1)[-9]	-	-		Est.
41.	$OONO^- + HNO_3 \rightarrow NO_3^- + NO + HO_2$	(1)[-9]	-	-		
42.	$CO_3^- + O \rightarrow O_2^- + CO_2$	(1.1)[-10.0±0.3]	-	-	See Reaction XII. 17	Chp. 18A
43.	$CO_3^- + H \rightarrow OH^- + CO_2$	(1.7)[-10.0±0.3]	-	-		Ref. 24-31
44.	$CO_3^- + NO \rightarrow NO_2^- + CO_2$	(1.1±0.3)[-11]	(-1.1)	0	T ≤ 600 K	Chp. 18A + Ref. 24-47
45.	$CO_3^- + NO_2 \rightarrow NO_3^- + CO_2$	(2.0±1.0)[-10]	0	0		Ref. 24-46
46.	$CO_3^- + N_2O \rightarrow CO_4^- + N_2$	-	-	-	k < (5)[-13]	Ref. 24-49
47.	$CO_3^- + HNO_2 \rightarrow NO_2^- + CO_2 + OH$	(1)[-9]	-	-		Est.
48.	$CO_3^- + HNO_3 \rightarrow NO_3^- + CO_2 + OH$	(8.0±3.0)[-10]	-	-		Ref. 24-25
49.	$CO_4^- + O \rightarrow CO_3^- + O_2$	(1.5±0.8)[-10]	-	-	Note ar	Chp. 18A
50.	$CO_4^- + H \rightarrow CO_3^- + OH$	(2.2)[-10.0±0.3]	-	-		Ref. 24-31
51.	$CO_4^- + O_2 \rightarrow O_4^- + CO_2$	(4.3)[-10]	0	3000	k_{300} (2.0)[-14]; Note [illegible]	Est.
52.	$CO_4^- + NO \rightarrow OONO^- + CO_2$	(4.8±2.0)[-11]	-	-		Chp. 18A

Table 24-1. (cantinued)

No.	Reaction	a	b	c	Notes	Sources
XVI.	Negative-Ion-Atom Interchange: (continued)					
53.	$CO_4^- + HNO_2 \rightarrow NO_2^- + CO_2 + HO_2$	(1)[-9]	-	-		Est.
54.	$CO_4^- + HNO_3 \rightarrow NO_3^- + CO_2 + HO_2$	(1)[-9]	-	-		
55.	$O_2^- \cdot H_2O + NO \rightarrow OONO^- + H_2O$	(3.1±1.0)[-10]	-	-		Chp. 18A
56.	$O_2^- \cdot H_2O + CO_2 \rightarrow CO_4^- + H_2O$	(5.8±1.0)[-10]	-	-		
57.	$NO_2^- \cdot H_2O + O_3 \rightarrow NO_3^- \cdot H_2O + O_2$	(1)[-11]	-	-		Gst.
58.	$NO_3^- \cdot H_2O + HNO_3 \rightarrow$ $NO_3^- \cdot HNO_3 + H_2O$	-	-	-	k = (5)[-10]	Ref. 24-25
59.	$CO_3^- \cdot H_2O + NO \rightarrow NO_2^- \cdot H_2O + CO_2$	(7.0±2.5)[-12]	0	0		Ref. 24-46
60.	$CO_4^- \cdot H_2O + NO \rightarrow NO_3^- \cdot H_2O + CO_2$	(1)[-11]	-	-		Gst.
XVII.	Radiation-Stabilized Positive-Ion-Neutral Association:					
1.	$X^+ + Y \rightleftharpoons (XY^+)^{\ddagger} \rightleftharpoons XY^+ + h\nu$	(1)[-19.0±0.5]	0	0	Monatomic reactants	Est.
		(1)[-15.0±0.5]	0	0	Diatomic reactants	
		(1)[-13.0±0.5]	0	0	Polyatomic and complex reactants	

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XVIII.	Positive-Ion Photodissociation:					
1.	$O_4^+ + h\nu \rightarrow O_2^+ + O_2$	$(3.2 \pm 1.3)(-1)$	0	0	Note as	Ref. 24-51
2.	$O_2^+ \cdot H_2O + h\nu \rightarrow O_2^+ + H_2O$	$(4.2 \pm 2.1)(-1)$	0	0		
3.	$NO^+ \cdot H_2O + h\nu \rightarrow NO^+ + H_2O$	$(2.0)(-2)$	0	0	Estimated value	Ref. 24-52
XIX.	Three-Body Positive-Ion-Neutral Association:					
1.	$O^+ + N_2 + M \rightarrow NO^+ + N + M$	$(6.0)(-29)$	(-2.0 ± 1.0)	0	Notes at, av; See Reaction XIV.2	Chp. 18A
2.	$N^+ + N_2 + M \rightarrow N_3^+ + M$	$(1.8 \pm 0.2)(-29)$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	M = N_2; Note at	Refs. 24-53, 24-54
3.	$O_2^+ + O_2 + M \rightarrow O_4^+ + M$	$(3.9)(-30)$	(-3.2 ± 0.5)	0	Notes av, aw	Ref. 24-55
4.	$O_2^+ + N_2 + M \rightarrow O_2^+ \cdot N_2 + M$	$(9.0)(-31)$	(-2.0 ± 1.0)	0	Notes at, ax	Chp. 18A
5.	$O_2^+ + O_3 + M \rightarrow O_5^+ + M$	$\left(1.0^{+3.0}_{-0.7}\right)(-28)$	-	-	M = He	Ref. 24-56
6.	$O_2^+ + H_2O + M \rightarrow O_2^+ \cdot H_2O + M$	$(2.8)(-28)$	(-2.0 ± 0.3)	0	M = N_2; Note av	Ref. 24-57
7.	$NO^+ + NO + M \rightarrow NO^+ \cdot NO + M$	$(5.0)(-30)$	(-2.0 ± 1.0)	0	M = NO; Note at	Chp. 18A
8.	$NO^+ + N_2 + M \rightarrow NO^+ \cdot N_2 + M$	$(2)(-31.0 \pm 0.2)$	(-4.4 ± 0.5)	0	M = N_2	Chp. 18A; Ref. 24-58
9.	$NO^+ + O_3 + M \rightarrow NO^+ \cdot O_3 + M$	$\left(1.0^{+3.0}_{-0.7}\right)(-29)$	-	-	M = He	Ref. 24-56
10.	$NO^+ + H_2O + M \rightarrow NO^+ \cdot H_2O + M$	$(1.5)(-28)$	(-2.0 ± 1.0)	0	M = N_2; Note at	Chp. 18A

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIX.	Three-Body Positive-Ion-Neutral Association: (continued)					
11.a	$NO^+ + CO_2 + M \rightarrow NO^+ \cdot CO_2 + M$	(3)[-29]	(-2.0±1.0)	0	Data at 200 K; M = N_2; Note at	Chp. 18A
b		(2)[-29]	(-2.3±1.5)	0	M = CO_2; Note at	Chp. 18A
12.	$N_2^+ + N_2 + M \rightarrow N_4^+ + M$	(5.0)[-29]	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	M = N_2; Note at	Chp. 18A
13.	$NO_2^+ + H_2O + M \rightarrow NO_2^+ \cdot H_2O + M$	(5.0)[-28]	(-2.0±1.0)	0	M = N_2; Note at	Ref. 24-25
14.	$H_3O^+ + N_2 + M \rightarrow H_3O^+ \cdot N_2 + M$	(1.4)[-30]	(-2.0±1.0)	0		Est.
15.a	$H_3O^+ + H_2O + M \rightarrow H_3O^+ \cdot H_2O + M$	(3.7)[-27]	(-2.0±1.0)	0	Data at 307 K; M = O_2; Note at	Chp. 18A
b		(3.4)[-27]	(-4.0±2.0)	0	M = N_2; Note at	Chp. 18A
16.	$NO^+ \cdot H_2O + N_2 + M \rightarrow NO^+ \cdot H_2O \cdot N_2 + M$	(2.0)[-31]	(-4.4±0.5)	0		Est.
17.	$NO^+ \cdot H_2O + H_2O + M \rightarrow NO^+(H_2O)_2 + M$	(1.1)[-27]	(-4.7±1.0)	0	M = N_2; Note at	Chp. 18A
18.	$NO^+ \cdot H_2O + CO_2 + M \rightarrow NO^+ \cdot H_2O \cdot CO_2 + M$	(2.0)[-29]	(-2.0±1.0)	0		Est.
19.	$NO^+(H_2O)_2 + N_2 + M \rightarrow NO^+(H_2O)_2N_2 + M$	(2.0)[-31±1]	(-4.4±1.0)	0		Est.

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XIX.	Three-Body Positive-Ion-Neutral Association: (continued)					
20.	$NO^+(H_2O)_2 + H_2O + M \rightarrow NO^+(H_2O)_3 + M$	(1.6) [-27]	(-4.7±1.0)	0	M N_2; Note at	Chp. 18A
21.	$NO^+(H_2O)_2 + CO_2 + M \rightarrow NO^+(H_2O)_2CO_2 + M$	(2.0) [-29±1]	(-2.0±1.0)	0		Gst.
22.	$NO_2^+ \cdot H_2O + H_2O + M \rightarrow NO_2^+(H_2O)_2 + M$	(2.0) [-27]	(-2.0±1.0)	0	M N_2; Note at	Ref. 24-25
23. a.	$H_3O^+ \cdot H_2O + H_2O + M \rightarrow H_3O^+(H_2O)_2 + M$	(2.0) [-27]	(-4.0±2.0)	0	Data at 307 K; M = O_2; Note at	Chp. 18A
b.		(2.3) [-27]	(-2.0±1.0)	0	M N_2; Note at	
24. a.	$H_3O^+(H_2O)_2 + H_2O + M \rightarrow H_3O^+(H_2O)_3 + M$	(2.0) [-27]	(-4.0±2.0)	0	Data at 307 K; M = O_2; Note at	
b.		(2.4) [-27]	(-2.0±1.0)	0	M N_2; Note at	
25.	$H_3O^+(H_2O)_3 + H_2O + M \rightarrow H_3O^+(H_2O)_4 + M$	(9.0) [-28]	(-4.0±2.0)	0	Data at 307 K; M = O_2; Note at	

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XX.	Positive-Ion Collisional Dissociation: (See Note ay)					
1.	$O_4^+ + M \rightarrow O_2^+ + O_2 + M$	(1)[-5 ± 1]	(-4.2 ± 0.2)	5400±300	Notes az, ba; k_{300} (3.9±2.0)[-13] or (2.8±1.4)[-13] for M = N_2 or O_2, respectively	Ref. 24-59
2.	$NO^+ \cdot NO + M \rightarrow NO^+ + NO + M$	(3.3 ± 2.3)[-5]	(-1)	7300±1000	k_{300} (9±2)[-16]; M = NO	Refs. 24-44, 24-60
3.	$NO^+ \cdot N_2 + M \rightarrow NO^+ + N_2 + M$	(1)[-8 ± 1]	(-5.4 ± 0.5)	2100±300	k_{300} (9±8)[-12]; M = N_2	Ref. 24-59
4.	$NO^+ \cdot H_2O + M \rightarrow NO^+ + H_2O + M$	(2)[-5]	(-1)	9300	Estimated value; k_{300} (7)[-19]	Ref. 24-61
5.	$NO^+ \cdot CO_2 + M \rightarrow NO^+ + CO_2 + M$	(2)[-5 ± 2]	(-3.3 ± 1.5)	5500±1300	Note bb; k_{300} (2.4±1.0)[-13] or (4.0±1.6)[-13] for M = N_2 or CO_2, respectively	Ref. 24-59
6.	$NO^+(H_2O)_2 + M \rightarrow NO^+ \cdot H_2O + H_2O + M$	(1)[-2 ± 1]	(-5.7 ± 1.0)	8100±500	k_{300} = (1.7 ± 0.5)[-14]; M = N_2; Note az	
7.	$NO^+(H_2O)_3 + M \rightarrow NO^+(H_2O)_2 + H_2O + M$	(1)[-2.0 ± 1.3]	(-5.7 ± 1.0)	6800±800	k_{300} (1.4±0.3)[-12] M = N_2; Notes az, bc	
8.	$NO^+ \cdot H_2O \cdot N_2 + M \rightarrow NO^+ \cdot H_2O + N_2 + M$	(5)[-8]	(-5.4)	2100	Estimated value; k_{300} = (5)[-11]	
9.	$NO^+ \cdot H_2O \cdot CO_2 + M \rightarrow NO^+ \cdot H_2O + CO_2 + M$	(2)[-4]	(-3.3)	5500	Estimated value; k_{300} = (2)[-12]	

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XX.	Positive-Ion Collisional Dissociation: (continued) (See Note ay)					
10.	$NO^+(H_2O)_2N_2 + M \rightarrow NO^+(H_2O)_2 + N_2 + M$	(5)[-7]	(-5.4)	2100	Estimated value; $k_{300} = (5)[-10]$	Ref. 24-59
11.	$NO^+(H_2O)_2CO_2 + M \rightarrow NO^+(H_2O)_2 + CO_2 + M$	(2)[-3]	(-3.3)	5500	Estimated value; $k_{300} = (2)[-11]$	
12.	$H_3O^+ \cdot N_2 + M \rightarrow H_3O^+ + N_2 + M$	(2)[-6]	(-5)	4500	Estimated value; k_{300} (6)[-13]	
13.	$H_3O^+ \cdot OH + M \rightarrow H_3O^+ + OH + M$	≈(5)[+1]	(-5 ± 2)	13,000±4000	$k_{300} \approx (7)[-18]$; M N_2; Note bd	
14.	$H_3O^+ \cdot H_2O + M \rightarrow H_3O^+ + H_2O + M$	(1)[-2.0 ± 1.5]	(-5 ± 2)	16,000±1000	$k_{300} \approx (7)[-26]$; M N_2; Note az	
15.	$H_3O^+(H_2O)_2 + M \rightarrow H_3O^+ \cdot H_2O + H_2O + M$	(2)[-3 ± 1]	(-5 ± 2)	10,000±600	k_{300} (7.0±2.8)[-18]; M N_2; Notes az, be	
16.	$H_3O^+(H_2O)_3 + M \rightarrow H_3O^+(H_2O)_2 + H_2O + M$	(1)[-1.0 ± 1.5]	(-5 ± 2)	8800±500	k_{300} (4.0±3.3)[-14]; M N_2; Note be	
17.	$H_3O^+(H_2O)_4 + M \rightarrow H_3O^+(H_2O)_3 + H_2O + M$	(1)[0.0 ± 1.3]	(-5 ± 2)	7700±700	Notes ba, be; k_{300} (8.4±3.6)[-12] or (6.0±2.6)[-12] for M N_2 or O_2, respectively	

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXI.	Radiation-Stabilized Negative-Ion-Neutral Association:					
1.	$O^- + O_2 \rightarrow O_3^- + h\nu$	(1)[-17±2]	0	0		Est.
XXII.	Negative-Ion Photodissociation:					
1.	$O_3^- + h\nu \rightarrow O^- + O_2$	(5±2)[-1]	-	-		Ref. 24-62
2.	$O_4^- + h\nu \rightarrow O_2^- + O_2$	$\left(3^{+3}_{-2}\right)$[-1]	-	-	Cf. Reaction VIII.6	Ref. 24-18
3.	$OONO^- + h\nu \rightarrow O_2^- + NO$	(7±2)[-2]	-	-	Estimated value	Ref. 24-63
4.	$CO_3^- + h\nu \rightarrow O^- + CO_2$	$\left(2^{+2}_{-1}\right)$[-1]	-	-		Ref. 24-62
5.	$CO_4^- + h\nu \rightarrow O_2^- + CO_2$	(1.4)[-2.0±0.3]	-	-		Ref. 24-64
6.	$O_2^- \cdot H_2O + h\nu \rightarrow O_2^- + H_2O$	(1.1)[-1.0±0.3]	-	-		Ref. 24-18
7.	$NO_2^- \cdot H_2O + h\nu \rightarrow NO_2^- + H_2O$	(2)[-1.0±0.7]	-	-		Ref. 24-64
8.	$NO_3^- \cdot H_2O + h\nu \rightarrow NO_3^- + H_2O$	(7)[-2.0±0.7]	-	-		Ref. 24-64
9.	$NO_3^- \cdot HNO_3 + h\nu \rightarrow NO_3^- + HNO_3$	(2)[-1.0±0.7]	-	-		Ref. 24-64
10.	$CO_3^- \cdot H_2O + h\nu \rightarrow CO_3^- + H_2O$	(1.0±0.5)[0]	-	-		Ref. 24-62
11.	$CO_4^- \cdot H_2O + h\nu \rightarrow CO_4^- + H_2O$	(2)[-1.0±0.7]	-	-		Ref. 24-64

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXIII.	Three-Body Negative-Ion-Neutral Association:					
1.	$O^- + O_2 + M \rightarrow O_3^- + M$	$(1.1 \pm 0.1)[-30]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	M = O_2; Note at	Chp. 18A
2.	$O^- + NO + M \rightarrow NO_2^- + M$	$(1)[-29 \pm 2]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	Notes at, bf	Est.
3.	$O^- + N_2 + M \rightarrow N_2O^- + M$	$(3)[-31]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	Data at 200 K; M = He; Note at	Chp. 18A
4.	$O^- + H_2O + M \rightarrow H_2O_2^- + M$	$(1.0)[-28]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	M = O_2; Note at	Ref. 24-46
5.	$O^- + CO_2 + M \rightarrow CO_3^- + M$	$(3.1)[-28]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0		
6.	$O_2^- + O_2 + M \rightarrow O_4^- + M$	$(3.5 \pm 0.5)[-31]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0		Chp. 18A
7.	$O_2^- + N_2 + M \rightarrow O_2^- \cdot N_2 + M$	$(3)[-32]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	Data at 200 K; M = He; Note at	
8.	$O_2^- + H_2O + M \rightarrow O_2^- \cdot H_2O + M$	$(3)[-28]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	M = O_2; Note at	
9.	$O_2^- + CO_2 + M \rightarrow CO_4^- + M$	$(2.0)[-29]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0		
10.	$O_3^- + H_2O + M \rightarrow O_3^- \cdot H_2O + M$	$(2.1)[-28]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0		
11.	$NO_2^- + H_2O + M \rightarrow NO_2^- \cdot H_2O + M$	$(1.3)[-28]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	M = NO; Note at	
12.	$NO_3^- + H_2O + M \rightarrow NO_3^- \cdot H_2O + M$	$(7.5)[-29]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	Note at	Ref. 24-65
13.	$CO_3^- + H_2O + M \rightarrow CO_3^- \cdot H_2O + M$	$(1.0)[-28]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	M = O_2; Note at	Ref. 24-46
14.	$CO_4^- + H_2O + M \rightarrow CO_4^- \cdot H_2O + M$	$(5.0)[-29]$	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	Estimated value; Note at	Ref. 24-64

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXIII.	Three-Body Negative-Ion-Neutral Association: (continued)					
15.	$O_2^- \cdot H_2O + H_2O + M \rightarrow O_2^-(H_2O)_2 + M$	(4)[-28]	$\left(-1.0^{+0.5}_{-1.0}\right)$	0	$M = O_2$; Note at	Chp. 18A
XXIV.	Negative-Ion Collisional Dissociation: (See Note ay)					
1.	$O_4^- + M \rightarrow O_2^- + O_2 + M$	$(2.2 \pm 1.3)[-5]$	(-1)	6300	$k_{300} = (1.7 \pm 1.0)[-14]$; $M = O_2$	Refs. 24-66 through 24-69
XXV.	Radiation-Stabilized Neutral Recombination:					
1.a.	$O + O \rightarrow O_2(A^3\Sigma_u^+) \rightarrow O_2 + h\nu$ (Herzberg)	(2.4±0.1)[-21]	0	0		Refs. 24-70, 24-71
b.	$\rightarrow O_2(b^1\Sigma_g^+) \rightarrow O_2 + h\nu$ (Atmospheric)	$(1.7 \pm 0.2)[-37] \cdot n_{N_2}$	0	0		Ref. 24-71
c.	$\rightarrow O_2(B^3\Sigma_u^-) \rightarrow O_2 + h\nu$ (Schumann-Runge)	(2)[-17]	0	12,000±1100	$k_{3000} = (3.7 \pm 1.5)[-19]$	Ref. 24-72
2.a.	$O + N \rightarrow NO(A^2\Sigma^+) \rightarrow NO + h\nu$ (Gamma)	$\left\{1.2 \times 10^{-17} \left(\frac{T}{300}\right)^{-0.35} + 2.1 \times 10^{-34} n_{N_2} \left(\frac{T}{300}\right)^{-1.24}\right\}$				Ref. 24-73
b.	$\rightarrow NO(B^2\Pi_r) \rightarrow NO + h\nu$ (Beta)	$(3.1 \pm 0.1)[-34] \cdot n_{N_2}$	(-1.4)	0		
c.	$\rightarrow NO(C^2\Pi) \rightarrow NO + h\nu$ (Delta)	(6.8±3.0)[-18]	(-0.35)	0		
3.a.	$O + NO \rightarrow NO_2 + h\nu$	(8±2)[-17]	(-2.0±0.5)	0	$p > 0.3$ torr	Chp. 19
b.		(7±2)[-18]	(-2.0±0.5)	0	$p \leq 10^{-3}$ torr	
4.	$N + N \rightarrow N_2 + h\nu$	(1.0±0.5)[-17]	(-0.90±0.05)	0		Ref. 24-74

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXVI.	Neutral Photodissociation: (See Notes s and bg)					
1. a.	$O_2 + h\nu \rightarrow O + O$	(8.4±2.5)[-8]	0	0		
b.	$\rightarrow O + O(^1D)$	(2.2±0.7)[-6]	0	0	Schumann-Runge	
2.	$NO + h\nu \rightarrow N + O$	(6.1±1.8)[-6]	0	0		
3. a.	$O_3 + h\nu \rightarrow O + O_2$	(4.5±0.9)[-4]	0	0		
b.	$\rightarrow O + O_2(a^1\Delta_g)$	(1.1±0.2)[-4]	0	0		
c.	$\rightarrow O(^1D) + O_2(a^1\Delta_g)$	(8.7±1.3)[-3]	0	0		
d.	$\rightarrow O(^1D) + O_2(b^1\Sigma_g^+)$	(4.8±1.2)[-4]	0	0		
4.	$NO_2 + h\nu \rightarrow NO + O$	(1.2±0.2)[-2]	0	0		Ref. 24-75
5.	$N_2O + h\nu \rightarrow N_2 + O(^1D)$	(2.0±0.4)[-6]	0	0		
6.	$HO_2 + h\nu \rightarrow OH + O$	(9.6±2.9)[-4]	0	0		
7.	$H_2O + h\nu \rightarrow H + OH$	(8.3±2.5)[-6]	0	0		
8. a.	$CO_2 + h\nu \rightarrow CO + O$	(1.1±0.6)[-8]	0	0		
b.	$\rightarrow CO + O(^1D)$	(9.4±4.7)[-8]	0	0		
9.	$OCS + h\nu \rightarrow CO + S$	(4.5±1.1)[-5]	0	0		
10.	$SO_2 + h\nu \rightarrow SO + O$	(1.0±0.4)[-4]	0	0		

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXVI.	Neutral Photodissociation: (continued) (See Notes s and bg)					
11.	$H_2S + h\nu \rightarrow H + SH$	(3.7±1.1)[-4]	0	0		Ref. 24-75
12.	$HNO_2 + h\nu \rightarrow OH + NO$	(8.9±2.7)[-4]	0	0		
13.	$H_2O_2 + h\nu \rightarrow OH + OH$	(7.1±2.1)[-5]	0	0		
14. a.	$HCHO + h\nu \rightarrow H + CHO$	(1.1±0.4)[-4]	0	0		
b.	$\rightarrow H_2 + CO$	(1.5±0.6)[-4]	0	0		
15.	$HNO_3 + h\nu \rightarrow OH + NO_2$	(1.6±0.3)[-4]	0	0		
16.	$CH_4 + h\nu \rightarrow \begin{Bmatrix} H + CH_3 \\ H_2 + CH_2 \end{Bmatrix}$	(4.0±2.0)[-6]	0	0		
17.	$N_2O_5 + h\nu \rightarrow$ Products	(6.6±1.7)[-4]	0	0		
XXVII.	Three-Body Neutral Recombination:					
1.	$O + O + O \rightarrow O_2 + O(^1S)$	(1.4)[-30.0±0.3]	0	650±300	$k_{300}=(1.6)^{-31.0\pm0.8}$; T = 200 - 400 K	Ref. 24-76
2.	$O + O + O_2 \rightarrow O_2(A^3\Sigma_u^+) + O_2$	(3)[-33.0±0.3]	0	0	T > 1000 K	Chp. 20
3. a.	$O + O + N_2 \rightarrow O_2 + N_2$	(4.80±0.36)[-33]	(-2.0)	0	T = 200 - 300 K	Ref. 24-77
b.		(1.3)[-33.0±0.3]	(-1.0)	170	T > 1000 K; T_{ref} = 3000 K; $k_{3000}=(1.2)^{-33.0\pm0.3}$	Ref. 24-78
c.	$\rightarrow O_2(A^3\Sigma_u^+) + N_2$	(2.1)[-37±1]	0	0		Chp. 20

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXVII.	Three-Body Neutral Recombination: (continued)					
3.d.	$C + O + N_2 \rightarrow O_2(b^1\Sigma_g^+) + N_2$	(1.7)[-37±1]	0	0		Chp. 20
4.	$O + N + O \rightarrow NO + O(^1S)$	(3)[-33±1]	0	0		Chp. 20
5.a.	$O + N + N_2 \rightarrow NO + N_2$	(1.0)[-32.0±0.2]	(-0.5)	0		Ref. 24-78
b.	$\rightarrow NO(8^2\Pi_r) + N_2$	(1) [-34±1]	0	0		Chp. 20
6.	$O + H + Ar \rightarrow OH + Ar$	(2.0)[-32±1]	0	0	T = 1000 - 3000 K	Ref. 24-78
7.a.	$N + N + N_2 \rightarrow N_2 + N_2$	(8.3)[-34.0±0.2]	0	-500	k_{300} = (4.4)[-33.0±0.2]	Ref. 24-78
b.		(4.6±0.2)[-33]	(-1.7)	0	T_{ref} = 3000 K	Chp. 19
c.	$\rightarrow N_2(8^3\Pi_g) + N_2$	(1.4)[-33±1]	0	0		Chp. 20
8.	$H + H + H_2 \rightarrow H_2 + H_2$	(8.3)[-33.0±0.5]	(-0.6±0.2)	0		Ref. 24-79
9.	$O + O_2 + M \rightarrow O_3 + M$	(1.1)[-34.00±0.07]	0	-510	k_{300} = (6 ± 1)[-34]; M=N_2 or O_2	Chp. 19 + Ref. 24-78
10.	$O + NO + N_2 \rightarrow NO_2 + N_2$	(1.55±0.20)[-32]	0	-584±35	T = 217 - 500 K; k_{300} = (1.09±0.30)[-31]	Ref. 24-80
11.	$O + OH + M \rightarrow HO_2 + M$	(1.0)[-31]	0	0	Estimated value	Ref. 24-61
12.	$O + CO + N_2 \rightarrow CO_2 + N_2$	(1.4±0.3)[-35]	0	0		Ref. 24-81
13.	$O + N_2 + M \rightarrow N_2O + M$	(1)[-34±2]	0	7500	k_{3000} = (8)[-36 ± 2]	Est.

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXVII.	Three-Body Neutral Recombination: (continued)					
14.	$O(^1D) + N_2 + M \rightarrow N_2O + M$	(2.8±1.4)[-36]	0	0		Ref. 24-82
15.	$H + O_2 + M \rightarrow HO_2 + M$	(2.1)[-32.00±0.07]	0	-290	T = 200 - 400 K; M = N_2 or O_2; k_{300} = (5.5 ± 1.0)[-32]	Chp. 19 + Ref. 24-78
16.	$H + NO + M \rightarrow HNO + M$	(2.1)[-32.0±0.2]	0	-300	T = 220 - 400 K; k_{300} = (5.7)[-32.0±0.2]	Ref. 24-78
17.	$H + OH + M \rightarrow H_2O + M$	(6.8)[-33.0 ± 0.3]	(-2.0)	0	T = 1000 - 3000 K; T_{ref} = 3000 K	
18.	$O + NO_2 + M \rightarrow NO_3 + M$	(1.0)[-31.0±0.2]	(-2.0)	0	Note bh	Refs. 24-61, 24-78
19.	$H + NO_2 + M \rightarrow HNO_2 + M$	(5.0)[-31]	(-2.4)	0	Estimated value	Ref. 24-61
20.	$NO + O_2 + M \rightarrow NO_3 + M$	(1.0)[-40]	0	0		
21.	$NO + OH + N_2 \rightarrow HNO_2 + N_2$	(5.8±1.2)[-31]	(-2.4)	0		Ref. 24-83
22.	$OH + OH + N_2 \rightarrow H_2O_2 + N_2$	(2.5±0.3)[-31]	(-2)	0	Note bi	Refs. 24-84, 24-85
23.	$OH + NO_2 + N_2 \rightarrow HNO_3 + N_2$	(2.2±0.5)[-30]	(-2.5)	0		Ref. 24-83
XXVIII.	Neutral Collisional Dissociation:					
1.	$O_2 + O_2 \rightarrow O + O + O_2$	(6.6±3.1)[-9]	(-1.5±0.5)	59,000	T = 3000 - 5000 K; T_{ref} = 3000 K; k_{3000} = (1.9±0.9)[-17]	Ref. 24-72
2.	$NO + M \rightarrow N + O + M$	(4.1±1.9)[-9]	(-1.5±0.5)	75,000	T = 3000 - 8000 K; M = O_2, N_2, Ar; T_{ref} = 3000 K; k_{3000} = (5.7±2.6)[-20]	Ref. 24-86

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXVIII.	Neutral Collisional Dissociation: (continued)					
3.	$N_2 + N_2 \rightarrow N + N + N_2$	$(3.5\pm0.9).-9^{*}$	(-1.6 ± 0.5)	113,000	T = 8000 - 15,000 K; T_{ref} = 8000 K; $k_{8000}=(2.6\pm0.7).-15^{*}$	Ref. 24-87
4.	$N_2 + Ar \rightarrow N + N + Ar$	$(1.3\pm0.2).-9^{*}$	(-1.6 ± 0.5)	113,000	T = 8000 - 15,000 K; T_{ref} = 8000 K; $k_{8000}=(9.5\pm1.5).-16^{*}$	Ref. 24-87
5.	$O_3 + O_2(a^1\Delta_g) \rightarrow O + O_2 + O_2$	$(4.5).-11^{*}$	0	2800±200	T = 283 - 321 K; $k_{300} = (4.0).-15.0\pm0.3^{*}$	Ref. 24-88
6.	$O_3 + O_2(b^1\Sigma_g^+) \rightarrow O + O_2 + O_2$	$(2.5\pm0.5).-11^{*}$	0	0		Ref. 24-89
7.	$O_3 + N_2 \rightarrow O + O_2 + N_2$	$(6.4\pm1.6).-10^{*}$	0	11,400	T = 200 - 1000 K; $k_{300}=(2.0\pm0.5).-26^{*}$	Ref. 24-90
8.	$NO_3 + M \rightarrow NO + O_2 + M$	$(9.0).-14^{*}$	(-1)	2100	Estimated value; $k_{300} = (8.2).-17^{*}$	Ref. 24-61
XXIX.	Neutral Rearrangement:					
1.	$O + NO \rightarrow N + O_2$	$(7.5).-12.00\pm0.11^{*}$	(1)	19,500	T = 1000 - 3000 K; T_{ref} = 3000 K; $k_{3000}=(1.1\pm0.3).-14^{*}$	Ref. 24-78
2.	$O + OH \rightarrow H + O_2$	$(4.2\pm1.7).-11.0\pm0.3^{*}$	0	0	T = 300 - 2000 K	Ref. 24-78
3.	$O + N_2 \rightarrow N + NO$	$(1.3).-10.0\pm0.3^{*}$	0	38,000	T = 2000 - 5000 K; $k_{3000}=(4.1).-16.0\pm0.3^{*}$	Ref. 24-78
4.	$O(^1D) + H_2 \rightarrow H + OH$	$(1.30\pm0.05).-10^{*}$	-	-		Ref. 24-91
5.	$O + O_3 \rightarrow O_2 + O_2$	$(1.9).-11.0\pm0.1^{*}$	0	2300	T = 220 - 1000 K; $k_{300} = (9\pm2).-15^{*}$	Ref. 24-78

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXIX.	Neutral Rearrangement: (continued)					
6.	$O(^1D) + O_3 \rightarrow O_2 + O_2$	$(2.4\pm0.1)[-10]$	-	-		Ref. 24-91
7.	$O + NO_2 \rightarrow O_2 + NO$	$(9.1\pm2.0)[-12]$	0	0		Chp. 19
8.	$O(^1D) + NO_2 \rightarrow O_2 + NO$	$(1.8\pm0.1)[-10]$	-	-	Note bj	Ref. 24-92
9.a.	$O + N_2O \rightarrow NO + NO$	$(1.5\pm0.5)[-10]$	0	$14,000\pm2000$	$k_{3000}=(1.4)[-12.0\pm0.4]$	Chp. 19
b.	$\rightarrow O_2 + N_2$	$(5\pm2)[-11]$	0	$14,000\pm2000$	$k_{3000}=(4.7)[-13.0\pm0.5]$	
10.	$O(^1D) + N_2O \rightarrow \begin{cases} NO + NO \\ O_2 + N_2 \end{cases}$	$(1.4\pm0.1)[-10]$	-	-		Ref. 24-91
11.	$O + HO_2 \rightarrow O_2 + OH$	$(8.0)[-11]$	0	500	Estimated value; $k_{300} = (1.5)[-11]$	Ref. 24-78
12.	$O(^1D) + H_2O \rightarrow OH + OH$	$(2.1\pm1.0)[-10]$	-	-		Ref. 24-91
13.	$O + NO_3 \rightarrow O_2 + NO_2$	$(1.0)[-12]$	0	1500	Estimated value; $k_{300} = (6.7)[-15]$	Ref. 24-61
14.	$O + H_2O_2 \rightarrow \begin{cases} OH + HO_2 \\ O_2 + H_2O \end{cases}$	$(2.75)[-12.00\pm0.07]$	0	2125	$k_{300} = (2.3\pm0.4)[-15]$	Ref. 24-78
15.	$O(^1D) + H_2O_2 \rightarrow \begin{cases} OH + HO_2 \\ O_2 + H_2O \end{cases}$	$\sim(5)[-10]$	0	0	Estimated value	
16.	$O + HNO_3 \rightarrow OH + NO_3$	-	-	-	Products uncertain; $k < (3)[-17]$	Ref. 24-94

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXIX.	Neutral Rearrangement: (continued)					
17.	$N + O_2 \rightarrow O + NO$	$(3.3)[-12.00\pm0.12]$	(1)	3150	T = 300 - 1500 K; $k_{300} = (9\pm3)[-17]$	Ref. 24-78
18.	$N(^2D) + O_2 \rightarrow O + NO$	$(7.5\pm0.5)[-12]$	(0.5)	0		Ref. 24-95
19.	$N + O_2(a^1\Delta_g) \rightarrow O + NO$	$(2.0\pm0.8)[-14]$	0	600	Products uncertain; $k_{300} = (2.7\pm1.1)[-15]$	Ref. 24-96
20.	$N + NO \rightarrow O + N_2^{\ddagger}(v=3-6)$	$(8.2\pm1.4)[-11]$	0	410±120	$k_{300}=(2.1)[-11.00\pm0.25]$	Ref. 24-97
21.	$N(^2D) + NO \rightarrow O + N_2$	$(6.0)[-11]$	0	0	Estimated value	Ref. 24-61
22.	$N + OH \rightarrow H + NO$	$(5.3)[-11.0\pm0.3]$	0	0		Ref. 24-78
23.	$N(^2D) + OH \rightarrow H + NO$	$(5.0)[-11]$	0	0	Estimated value	Ref. 24-61
24.	$N + O_3 \rightarrow O_2 + NO$	$(5.7)[-13.0\pm0.2]$	0	0		Ref. 24-78
25.	$N + NO_2 \rightarrow O + N_2O$	$(2.0\pm0.2)[-11]$	0	800	Note bk; $k_{300} = (1.4\pm0.1)[-12]$	Refs. 24-85, 24-97
26.a.	$N(^2D) + NO_2 \rightarrow O + N_2O$	$(1.0)[-10]$	0	0	Estimated value	Ref. 24-61
b.	$\rightarrow NO + NO$	$(1.0)[-10]$	0	0		
27.	$N + HO_2 \rightarrow NO + OH$	$(2.0)[-11]$	0	0		
28.	$N(^2D) + HO_2 \rightarrow NO + OH$	$(2.0)[-11]$	0	0		
29.	$H + O_2 \rightarrow O + OH$	$(3.7)[-10.0\pm0.1]$	0	8450	T = 700 - 2500 K; $k_{3000}=(2.2\pm0.6)[-11]$	Ref. 24-78
30.	$H + OH \rightarrow O + H_2$	$(4.2)[-12.00\pm0.15]$	(1)	3500	T = 400 - 2000 K; $k_{300}=(3.6)[-17.00\pm0.15]$	

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXIX.	Neutral Rearrangement: (continued)					
31.	$H + O_3 \rightarrow O_2 + OH$	$(1.23)[-10]$	0	562± 144	$k_{300}=(1.9)[-11.0\pm0.2]$	Ref. 24-98
32.	$H + NO_2 \rightarrow NO + OH$	$(4.9)[-10]$	0	412± 115	$k_{300}=(1.2)[-10.0\pm0.2]$	
33.	$H + N_2O \rightarrow OH + N_2$	$(1.26)[-10.0\pm0.2]$	0	7600	T = 700 - 2500 K; $k_{3000}=(1.0)[-11.0\pm0.2]$	Ref. 24-78
34.a.	$H + HO_2 \rightarrow OH + OH$	$(4.2)[-10.0\pm0.3]$	0	950	T = 290 - 800 K; $k_{300}=(1.8)[-11.0\pm0.3]$	Ref. 24-99
b.	$\rightarrow O_2 + H_2$	$(4.2)[-11.0\pm0.4]$	0	350	T = 290 - 800 K; $k_{300}=(1.3)[-11.0\pm0.4]$	
c.	$\rightarrow O + H_2O$	$(8.3)[-11.0\pm0.5]$	0	500	T = 300 - 1000 K; $k_{300}=(1.6)[-11.0\pm0.5]$	Ref. 24-78
35.a.	$H + H_2O_2 \rightarrow H_2 + HO_2$	$(2.3\pm1.3)[-12]$	0	1400± 140	T = 283 - 353 K; $k_{300}=(2.2)[-14.0\pm0.5]$	Refs. 24-100, 24-101
b.	$\rightarrow OH + H_2O$ (See Note bf)	$(2.9\pm1.3)[-12]$	0	1400± 140	T = 283 - 353 K; $k_{300}=(2.7)[-14.0\pm0.5]$	
36.	$O_2 + 2\,NO \rightarrow NO_2 + NO_2$	$(3.3)[-39.0\pm0.2]$	0	-530	$k_{300}=(1.9)[-38.0\pm0.2]$	Ref. 24-78
37.	$NO + O_3 \rightarrow O_2 + NO_2$	$(2.1)[-12.00\pm0.16]$	0	1450	T = 203 - 361 K; $k_{300}=(1.7)[-14.00\pm0.16]$	Ref. 24-102
38.	$NO + HO_2 \rightarrow OH + NO_2$	$(8\pm3)[-12]$	-	-	Note bm	Refs. 24-103, 24-104
39.	$NO + NO_3 \rightarrow NO_2 + NO_2$	$(2.0)[-11]$	0	0	Estimated value	Ref. 24-61

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXIX.	Neutral Rearrangement: (continued)					
40.	$OH + OH \rightarrow O + H_2O$	$(1.0)[-11.0\pm0.2]$	0	550	$T = 300 - 2000$ K; $k_{300}=(1.6)[-12.0\pm0.2]$	Ref. 24-78
41.	$OH + CO \rightarrow H + CO_2$	$(1.4)[-13.0\pm0.1]$	0	0	$T = 200 - 400$ K	
42.	$OH + H_2 \rightarrow H + H_2O$	$(3.6)[-11.00\pm0.08]$	0	2590	$T = 300 - 2500$ K; $k_{300}=(6.4\pm1.3)[-15]$	Ref. 24-78
43.	$OH + O_3 \rightarrow O_2 + HO_2$	$(1.5)[-12.0\pm0.3]$	0	1000	$T = 220 - 450$ K; $k_{300}=(5.4)[-14.0\pm0.3]$	Ref. 24-102
44.	$OH + HO_2 \rightarrow O_2 + H_2O$	$(3)[-11.0\pm0.5]$	-	-		
45.	$OH + HNO_2 \rightarrow NO_2 + H_2O$	$(2.1\pm0.2)[-12]$	0	0		Ref. 24-78
46.	$OH + H_2O_2 \rightarrow HO_2 + H_2O$	$(1)[-11.0\pm0.3]$	0	750	$T = 300 - 670$ K; $k_{300}=(8.2)[-13.0\pm0.3]$	Ref. 24-102
47.	$OH + HNO_3 \rightarrow H_2O + NO_3$	$(8.9\pm1.3)[-14]$	0	0		Ref. 24-110
48.	$O_3 + NO_2 \rightarrow O_2 + NO_3$	$(1.2)[-13.0\pm0.1]$	0	2450	$T = 220 - 340$ K; $k_{300}=(3.4\pm0.9)[-17]$	Ref. 24-78
49.	$O_3 + HO_2 \rightarrow 2O_2 + OH$	$(1.0)[-13.0\pm0.3]$	0	1250	$T = 225 - 298$ K; $k_{300}=(1.6)[-15.0\pm0.3]$	
50.	$NO_2 + HO_2 \rightarrow O_2 + HNO_2$	$\sim(3.0)[-14]$	-	-		
51	$HO_2 + HO_2 \rightarrow O_2 + H_2O_2$	$(7.5)[-12.0\pm0.6]$	0	500	$T = 300 - 1000$ K; $k_{300}=(1.4)[-12.0\pm0.6]$	Ref. 24-102
52.	$NO_3 + NO_3 \rightarrow O_2 + 2NO_2$	$(5.0)[-12.0\pm0.5]$	0	3000	$T = 293 - 309$ K; $k_{300}=(2.3)[-16.0\pm0.5]$	Ref. 24-78

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXX.	Radiative Electronic-State Deexcitation:					
1.	$O(^1D) \rightarrow O + h\nu$	(6.8±2.0)[-3]	0	0		Chp. 20
2.	$O(^1S) \rightarrow O + h\nu$	(1.35±0.40)[0]	0	0	Note bn	
3. a.	$O^+(^2D)_{5/2} \rightarrow O^+ + h\nu$	(4.8)[-5.0±0.3]	0	0		
b.	$O^+(^2D)_{3/2} \rightarrow O^+ + h\nu$	(1.7)[-4.0±0.3]	0	0		
4. a.	$O^+(^2P)_{3/2} \rightarrow O^+ + h\nu$	(2.4)[-1.0±0.3]	0	0		
b.	$O^+(^2P)_{1/2} \rightarrow O^+ + h\nu$	(1.9)[-1.0±0.3]	0	0		
5. a.	$N(^2D)_{3/2} \rightarrow N + h\nu$	(1.6)[-5.0±0.3]	0	0		
b.	$N(^2D)_{1/2} \rightarrow N + h\nu$	(7.1)[-6.0±0.3]	0	0		
6.	$N(^2P) \rightarrow N + h\nu$	(7.7)[-2.0±0.3]	0	0		
7.	$N^+(^1D) \rightarrow N^+ + h\nu$	(4.0)[-3.0±0.3]	0	0		
8.	$N^+(^1S) \rightarrow N^+ + h\nu$	(1.1)[0.0±0.3]	0	0		
9.	$O_2(a^1\Delta_g) \rightarrow O_2 + h\nu$	(2.6±1.0)[-4]	0	0	Note bn	
10.	$O_2(b^1\Sigma_g^+) \rightarrow O_2 + h\nu$	(8.3)[-2.0±0.3]	0	0		
11. a.	$N_2(A^3\Sigma_u^+)(F_2) \rightarrow N_2 + h\nu$	(7.7)[-1.0±0.3]	0	0		
b.	$N_2(A^3\Sigma_u^+)(F_1, F_3) \rightarrow N_2 + h\nu$	(3.7)[-1.0±0.3]	0	0		

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXX.	Radiative Electronic-State Deexcitation: (continued)					
12.	$NO(a^4\Pi_i) \rightarrow NO + h\nu$	$(6.3)[0.0\pm0.3]$	0	0		Chp. 20
13.	$NO_2(^2B_1) \rightarrow NO_2 + h\nu$	$(1.4\pm0.2)[+4]$	0	0		Chp. 20
XXXI.	Electronic-State Photoexcitation:					
1.a.	$O_2 + h\nu \rightarrow O_2(a^1\Delta_g)$				Note c	
b.	$\rightarrow O_2(b^1\Sigma_g^+)$				Note c	
XXXII.	Collisional Electronic-State Quenching:					
1.	$O(^1D) + e \rightarrow O(^3P) + e$	$(7.80\pm1.36)[-9]$	(-0.083 ± 0.085)	3993 ± 1649	Notes bo, bq; $T = T_e = 1160\text{-}232{,}000$ K; $T_{ref} = 3000$ K; $k_{3000} = (2.1)[-9.0\pm0.3]$	Ref. 24-111 + Calc. (Note bp)
2.	$O(^1D) + O_2 \rightarrow O + O_2(b^1\Sigma_g^+)$	$(4.1\pm0.5)[-11]$	-	-	Note bo	Ref. 24-91
3.	$O(^1D) + N_2 \rightarrow O + N_2$	$(3.0\pm0.1)[-11]$	-	-	Note bo	Ref. 24-91
4.	$O(^1D) + CO_2 \rightarrow O + CO_2$	$(1.20\pm0.09)[-10]$	-	-	Note bo	Ref. 24-91
5.a.	$O(^1S) + e \rightarrow O(^3P) + e$	$(3.16\pm0.33)[-9]$	(0.087 ± 0.052)	1299 ± 987	Note bq; $T = T_e = 1160\text{-}232{,}000$ K; $T_{ref} = 3000$ K; $k_{3000} = (2.1)[-9.0\pm0.2]$	Ref. 24-111 + Calc. (Note bp)
b.	$\rightarrow O(^1D) + e$	$(9.40\pm0.40)[-9]$	(-0.206 ± 0.032)	12840 ± 352	Note bq; $T = T_e = 1160\text{-}232{,}000$ K; $T_{ref} = 3000$ K; $k_{3000} = (1.3\pm0.2)[-10]$	Ref. 24-111 + Calc. (Note bp)

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXXII.	Collisional Electronic-State Quenching: (continued)					
6.	$O(^1S) + O(^3P) \rightarrow \begin{Bmatrix} O(^1D) + O(^1D) \\ O(^1D) + O(^3P) \end{Bmatrix}$	$(7.5)[-12.0\pm0.2]$	-	-		Chp. 20 + Ref. 24-78
7.	$O(^1S) + O_2 \rightarrow O + O_2$	$(4.3)[-12.00\pm0.15]$	0	850	T = 200 - 377 K; $k_{300}=(2.5)[-13.00\pm0.15]$	Ref. 24-78
8.	$O(^1S) + N_2 \rightarrow O + N_2$	-	-	-	$k < (1)[-17]$	Ref. 24-71
9.	$O(^1S) + H_2O \rightarrow O + H_2O$	$(3\pm2)[-10]$	0	0		Refs. 24-113, 24-114
10.	$O(^1S) + CO_2 \rightarrow O + CO_2$	$(3.1)[-11.00\pm0.15]$	0	1320	T = 200 - 450 K; $k_{300}=(3.8)[-13.00\pm0.15]$	Ref. 24-78
11.	$O^+(^2D) + e \rightarrow O^+ + e$	$(6.75\pm3.38) \times 10^{-12}\left(\frac{T_e}{300}\right)^{-0.5}$				Ref. 24-111
12.	$N(^2D) + e \rightarrow N(^4S) + e$	$(4.32\pm0.25)[-9]$	(-0.116 ± 0.041)	3551 ± 93	$T=T_e=1160-232{,}000$ K; $T_{ref}=3000$ K; $k_{3000}=(1.3\pm0.1)[-9]$	Ref. 24-111 + Calc. (Note bp)
13.	$N(^2D) + N_2 \rightarrow N + N_2$	-	-	-	$k < (6)[-15]$	Ref. 24-115
14.a.	$N(^2P) + e \rightarrow N(^4S) + e$	$(4.23\pm0.72)[-9]$	(-0.164 ± 0.065)	4461 ± 1816	$T=T_e=1160-232{,}000$ K; $T_{ref}=3000$ K; $k_{3000}=(9.6)[-10.0\pm0.3]$	Ref. 24-111 + Calc. (Note bp)
b.	$\rightarrow N(^2D) + e$	$(1.47\pm0.05)[-8]$	(-0.069 ± 0.035)	1481 ± 307	$T=T_e=1160-232{,}000$ K; $T_{ref}=3000$ K; $k_{3000}=(9.0\pm1.3)[-9]$	
15.	$O_2(a^1\Delta_g) + e \rightarrow O_2 + e$	$(1)[-11\pm1]$	0	0	Notes r, br	Ref. 24-116 + Chp. 20 (Fig. 20-8) + Est.

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXXII.	Collisional Electronic-State Quenching: (continued)					
16.	$O_2(a^1\Delta_g) + O \rightarrow O_2 + O$	-	-	-	$k < (1)[-16]$; Note br	Chp. 20
17.	$O_2(a^1\Delta_g) + O_2 \rightarrow O_2 + O_2$	$(2.2)[-18.0 \pm 0.1]$	(0.8)	0	Note br	Ref. 24-78
18.	$O_2(a^1\Delta_g) + O_2(a^1\Delta_g) \rightarrow O_2 + O_2(b^1\Sigma_g^+)$	$(2)[-18 \pm 1]$	0	0		Ref. 24-117
19.	$O_2(a^1\Delta_g) + N_2 \rightarrow O_2 + N_2$	-	-	-	$k < (2)[-20]$; Note br	Ref. 24-78
20.	$O_2(a^1\Delta_g) + O_3 \rightarrow O_2 + O + O_2$	$(4.5)[-11.00 \pm 0.11]$	0	2830	$T = 283 - 321$ K; $k_{300} = (3.6 \pm 1.0)[-15]$; Note br	
21.	$O_2(b^1\Sigma_g^+) + O_2 \rightarrow O_2 + O_2$	$(1.5)[-16.00 \pm 0.12]$	0	0		Ref. 24-78
22.	$O_2(b^1\Sigma_g^+) + N_2 \rightarrow O_2 + N_2$	$(2.0)[-15.0 \pm 0.1]$	0	0		
23.	$O_2^+(a^4\Pi_u) + O_2 \rightarrow O_2^+ + O_2$	$(3.1 \pm 1.5)[-10]$	0	0	$T - T_i < 2000$ K; See Reaction XIII.19.	Ref. 24-36
24.	$N_2(A^3\Sigma_u^+) + O \rightarrow \begin{Bmatrix} N_2 + O \\ NO + N \end{Bmatrix}$	-	-	-	$k \leq (3)[-11]$; Note bs	Chp. 20 (Table 20-4)
25.	$N_2(A^3\Sigma_u^+) + N \rightarrow N_2 + N$	$(5)\left[-11^{+0}_{-1}\right]$	0	0		
26.	$N_2(A^3\Sigma_u^+) + O_2 \rightarrow N_2 + O_2$	$(3.8 \pm 2.0)[-12]$	0	0		
27.	$N_2(A^3\Sigma_u^+) + NO \rightarrow N_2 + NO$	$(7 \pm 4)[-11]$	0	0		
28.	$N_2^+(A^2\Pi_u) + N_2 \rightarrow N_2^+ + N_2$	$(1)[-9 \pm 1]$	0	0		Chp. 20
29.	$N_2^+(B^2\Sigma_u^+) + O_2 \rightarrow N_2^+ + O_2$	$(2)[-9 \pm 1]$	0	0		

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXXII.	Collisional Electronic-State Quenching: (continued)					
30.	$N_2^+(B^2\Sigma_u^+) + N_2 \rightarrow N_2^+ + N_2$	$(6)[-10 \div 1]$	0	0		Chp. 20
XXXIII.	Radiative Vibrational-State Deexcitation:					
1.	$CO(v=1) \rightarrow CO(v=0) + h\nu$	$(3.3 \pm 0.3)[+1]$	0	0		Chp. 11
2.	$CO_2(001) \rightarrow CO_2(000) + h\nu$	$(4.00 \pm 0.20)[+2]$	0	0		Chp. 11
XXXIV.	Collisional Vibrational-State Quenching:					
1.	$O_2(v=1) + M \rightarrow O_2(v=0) + M$	$\left\{\frac{2.5 \times 10^{-12} T \exp[-2.95 \times 10^6/T]^{1/3}}{[1 - \exp(-2270/T)]}\right\}$			$M = N_2$ or O_2; $T = 800 - 3200$ K; $k_{3000} = (6.78)[-13]$	Chp. 20 (Table 20-5)
2.a.	$O_2(v=1) + O \rightarrow O_2(v=0) + O$	$(5.7 \pm 3.0)[-12]$	(-0.5)	483	$T = 300 - 1700$ K; $k_{300} = (1.1 \pm 0.6)[-12]$	Chp. 20 (Table 20-5)
b.		$(1.7 \pm 0.5)[-10]$	0	4000	$T = 2000 - 4000$ K; $k_{3000} = (4.5 \pm 1.3)[-11]$	Chp. 20 (Table 20-5)
3.	$N_2(v=1) + O \rightarrow N_2(v=0) + O$	$\left\{\frac{6.21 \times 10^{-14} T \exp[-1.37 \times 10^5/T]^{1/3}}{[1 - \exp(-3390/T)]}\right\}$ or $\left\{\frac{3.43 \times 10^{-12} T \exp[-3.74 \times 10^6/T]^{1/3}}{[1 - \exp(-3390/T)]}\right\}$			$T = 3000 - 4500$ K; $k_{3000} = (7.71)[-12]$ $T = 3000 - 4500$ K; $k_{3000} = (3.22)[-13]$	Chp. 20 (Table 20-2)
4.	$N_2(v=1) + N_2 \rightarrow N_2(v=0) + N_2$	$\left\{1.3 \times 10^{-11} T \exp[-1.06 \times 10^7/T]^{-1/3}\right\}$			$T = 300 - 5000$ K; $k_{300} = (2.2)[-23]$; $k_{3000} = (9.5)[-15]$	Chp. 20 (Table 20-2)

Table 24-1. (continued)

No.	Reaction	a	b	c	Notes	Sources
XXXV.	Collisional Vibrational Energy Exchange:					
1.	$O_2(v=1) + H_2O \rightarrow O_2(v=0) + H_2O(0^{\cdot}0)$	$(1.7)[-11 \pm 1]$	(-0.5)	0	Note bt	Chp. 20 (Table 20-5)
2.	$N_2(v=1) + O_2(v=0) \rightarrow N_2(v=0) + O_2(v=1)$	$\left\{\frac{2.5 \times 10^{-7} \exp.-1.82 \times 10^{7}/T]^{-1/3}}{[1 - \exp(-3390/T)]}\right\}$			T = 1000 - 10,000 K; $k_{3000} = (1.3)[-11]$	Chp. 20 (Table 20-2)
3.	$N_2(v=1) + N_2(v=0) \rightarrow N_2(v=0) + N_2(v=1)$	$(3)\left[-13.0^{+1.5}_{-0.3}\right]$	0	0	Note bu	
4.	$N_2(v=1) + CO_2(000) \rightarrow N_2(v=0) + CO_2(001)$	$(6 \pm 2)[-13]$	(-0.5)	0	T = 300 - 1200 K	

NOTES

a - Very small compared to dissociative recombination (Section IV).

b - "Top of the atmosphere" calculation from Chapter 13 data.

c - Wavelength and flux dependent.

d - For $T_{iv} > \sim 1000$ K, multiply given k by a factor $[1-\exp(-2677/T_{iv})]$ (Gst.).

e - Branching measured at 300 K; branching ratio should change with T.

f - For $T_{iv} > \sim 1300$ K, multiply given k by a factor $[1-\exp(-3230/T_{iv})]$ (Gst.).

g - According to Ref. 24-3, this represents the theoretical state prediction at 300 K, where (80±15)% of total recombination is for ions in the ground or first vibrational state, and respective yields of $N(^2D)$ are 67 or 98% by adiabatic calculation, 94 or 58% by diabatic calculation. Ref. 24-6 gives fraction of $N(^2D)$ as 0.76±0.06 from time-dependent resonance absorption data. The chapter authors have consulted H.H. Michels, M.A. Biondi, and M. Scheibe, and ascertained: (a) for the theoretical case where purely $NO^+(v=0)$ produces purely $N(^2D)$, $k = (1.2\pm0.3)\times10^{-7} \cdot (T_e/300)^{\left(-0.4^{+0.2}_{-0.1}\right)}$; (b) for the reverse reaction (associative ionization) $N(^2D) + O \rightarrow NO^+ + e$, calculated by detailed balance:

$k = (7.6\pm0.3) \times 10^{-13} (T/300)^{\left(0.6^{+0.2}_{-0.1}\right)} \exp(-4416/T)$ at $T \leq 1300$ K; $k_{300} = (3.1\pm0.1) \times 10^{-19}$

$k = (2.0\pm0.1)\times10^{-12}(T/1500)^{\left(0.6^{+0.2}_{-0.1}\right)}\exp(-4416/T)[1 - \exp(-3230/T)]$ at $1300\ K \leq T \leq 2000$ K; $k_{1500} = (9.3\pm0.5)\times10^{-14}$

$k = (3.9\pm0.5)\times10^{-12}(T/3000)^{\left(1.1^{+0.2}_{-0.1}\right)}\exp(-4416/T)[1 - \exp(-3230/T)]$ at $2000\ K \leq T \leq 6000$ K; $k_{3000} = (5.9\pm0.8)\times10^{-13}$

h - For $T_{iv} > \sim 1200$ K, multiply given k by a factor $[1-\exp(-3162/T_{iv})]$ (Gst.).

i - Theoretical branching ratio (Est. Ref. 24-7).

j - Temperature dependence may be steeper for T<200 K.

NOTES (continued)

k - Temperature dependences estimated by anology with $NH_4^+(NH_3)_n$ series (Ref. 24-9).

ℓ - Measured temperature dependence (Ref. 24-10).

m - For the analogous reactions for higher hydrates, i.e., $H_3O^+(H_2O)_n + e \rightarrow (n+1)H_2O + H$, where $n \geq 6$, use the rate coefficients for Reaction IV.28.

n - Values based on afterglow results, omitting the merged-beam results of Peterson, Moseley, et al. (Refs. 24-12, 24-13). The much larger values, e.g., $(5\text{-}8) \times 10^{-7} cm^3 sec^{-1}$ at 300 K, obtained in the latter works may result from the presence in the beams of molecular ions in vibrationally and rotationally excited states (Ref. 24-14). Such excited states are not normally expected in the atmosphere.

o - X^+ and Y^- are either atomic or molecular, including clustered species.

p - X^+, Y^-, and M are either atomic or molecular "air" species.

q - X^+(cluster) and Y^-(cluster) are any clustered ions.

r - Detailed balance calculation.

s - Values are for normal-incidence unattenuated solar flux at top of earth's atmosphere.

t - Based on experimental data and theoretical extrapolation.

u - Varies with altitude and solar zenith angle.

v - No experimental data.

w - Observed to be a saturated three-body process; k is the effective two-body value, in units of $cm^3 sec^{-1}$.

x - May react if N_2 is vibrationally excited.

y - Non-isothermal condition, i.e., if $T_V \neq T_i$, transition temperature between the two sets of parameters decreases below 1000 K. See Reaction XIV.1.

z - The sum of Reactions XIII.10 and XIV.6 represent one overall reaction, as measured experimentally, for which the division into the channels indicated is somewhat uncertain, and for which the energy dependence of the

NOTES (continued)

separate branches has not been measured. The rate constants k_Σ for the overall process (both reactions) in the respective temperature ranges are:

$$k_\Sigma = (5.5 \pm 0.5) \times 10^{-10} \left(\frac{T_i}{300}\right)^{\left(0.00^{+0.20}_{-0.17}\right)} \quad \text{at } T_i < 4600 \text{ K};$$

$$k_\Sigma = (1.2 \pm 0.2) \times 10^{-10} \left(\frac{T_i}{300}\right)^{(0.57 \pm 0.05)} \quad \text{at } T_i > 4600 \text{ K}.$$

These values have been arbitrarily halved between the two channels, as seemingly the most reasonable resolution of the problem at this time (Ref. 24-33).

aa - $N(^2D)$ is a probable product.

ab - Reported as a quenching reaction. See Reaction XXXII. 23.

ac - $N_2(A\,^3\Sigma_u^+)$ or $NO^+(a\,^3\Sigma^+)$ may be formed.

ad - Rate constant k_Σ for the sum of reactions XIII. 34 and XIV. 22 is:

$$k_\Sigma = 2.2 \times 10^{-9}.$$

ae - Temperature dependence may be based on T_i or T_v interchangeably, since both are in agreement within the limits of experimental error (Ref. 24-27). Values shown may be a lower limit (Ref. 24-39). They have been determined using monatomic buffer gases, e.g., He, Ar, and may vary for diatomic buffer gases, e.g., N_2 (Ref. 24-40). See also Reaction XIX. 1.

af - Not detected for kinetic energies $< \approx 5$ eV.

ag - Endothermic by 0.163 eV.

ah - Chp. 18A gives k < (1)[-15].

ai - Some $N(^2D)$ produced.

aj - Branching ratio uncertain.

ak - The k values indicated for the three branches are not necessarily equal. Their measured sum is: k_Σ = (1)[-10]. However, secondary reactions are possible and may be a factor in determining the products observed.

al - Products uncertain; compare Reactions XV. 16 and XVI. 15.

NOTES (continued)

am - Products may include $O_3^- \cdot H_2O$.

an - Ref. 24-50 identifies products as NO_3^- + O. This is incorrect.

ao - When $T - T_g < 600$ K, the "b" parameter = (-0.64) (Ref. 24-28).

ap - Reactions XVI. 36, 39 are both important as reverse processes to Reaction XVI. 24.

aq - A minor product channel may be: $2O_2 + O^-$.

ar A minor product channel may be: $CO_2 + O_3^-$.

as - Extrapolated from experimental data where $680 \leq \lambda \leq 440$ nm; error overestimated to compensate.

at - Value of "b" parameter estimated.

au - Recalculated for M = N_2 at 300 K, from measured rate constant $k = 5.4 \times 10^{-29} cm^6 sec^{-1}$ at 82 K, where M = He. N_2O^+ appears to predissociate.

av - Error limits indicated for "b" parameter have been estimated by Handbook Editor.

aw - Recalculated for M = N_2, from measured rate constant $k = 2.6 \times 10^{-30} (T/300)^{(-3.2)} cm^6 sec^{-1}$, where M = O_2.

ax - Recalculated for M = N_2 at 300 K, from measured rate constant $k = 8.4 \times 10^{-31} cm^6 sec^{-1}$ at 200 K, where M = He.

ay - In Sections XX and XXIV, the "a" parameters have usually been obtained by back-calculation from measured or estimated values of the respective "c" parameters and of the corresponding rate constants at or very near 300 K, i.e., k_{300} values, as referenced in each instance.

az - Error limits of "c" parameter have been estimated.

ba - Calculated for M = N_2 from measurements where M = O_2.

bb - Calculated for M = N_2 from measurements where M = CO_2.

bc - The "b" parameter has been based on the corresponding value for Reaction XX. 6, but may be more steeply negative.

bd - The "b" parameter has been based on the corresponding value for Reaction XX. 15.

NOTES (continued)

be - The "b" parameter has been based on the corresponding value for Reaction XX.14, but may be more steeply negative.

bf - Reaction XII.5 is dominant.

bg - Rates and uncertainties beneath the "top of the atmosphere" vary with altitude and solar zenith angle (Ref. 24-75).

bh - The "a" parameter is taken from Ref. 24-78; the "b" parameter is estimated from Ref. 24-61.

bi - The "a" parameter is taken from Ref. 24-84; the "b" parameter is estimated from Ref. 24-85.

bj - Based on $k = (1.20 \pm 0.09) \times 10^{-10}$ for $O(^1D) + CO_2$ (from Ref. 24-91) and the ratio $k[O(^1D)+NO_2]/k[O(^1D)+CO_2] = 1.5$ (from Ref. 24-93).

bk - Value of k_{300} is from Ref. 24-97; "c" parameter estimated by Ref. 24-85.

bℓ - Value of $k_\Sigma = (5.2 \pm 2.0) \times 10^{-12}$ from Ref. 24-100; ratio of k_{300} values, channel (b) to channel (a), = 1.3 from Ref. 24-101.

bm - This is an entirely new rate constant, much higher than has been reported previously, and substantiation for which is provided to two sets of considerations:

(i) Certain other values reported for the rate constant of Reaction XXIX.38 have depended on observed rate ratios within systems of competing reactions, viz., Reaction XXIX.38 ($NO + HO_2 \rightarrow OH + NO_2$) vs. Reaction XXIX.51 ($HO_2 + HO_2 \rightarrow O_2 + H_2O_2$) (Refs. 24-105 through 24-108), where monitoring of the NO-NO_2 conversion was a critical factor in calculating the values reported for Reaction XXIX.38, e.g., $k = 1.2 \times 10^{-11} \exp(-700 \pm 250)/T$, $k_{300} = 1.2 \times 10^{-(12.0 \pm 0.4)}$ $cm^3 sec^{-1}$ (Ref. 24-108). A still lower rate constant for the same reaction had been reported, i.e., $k = (2.0 \pm 0.5) \times 10^{-11} \exp(-1200 \pm 150)/T$, $k_{300} = 3.7 \times 10^{-(13.0 \pm 0.3)}$ $cm^3 sec^{-1}$ (Ref. 24-109), where monitoring depended on the observed rate of OH production. Either of these results would, however, be expected to have been artificially lowered by virtue of the competing fast Reaction XXIX.44 ($OH + HO_2 \rightarrow O_2 + H_2O$) (Ref. 24-103).

NOTES (continued)

(2) The recent work of C. J. Howard (Ref. 24-103) was based on three different determinations involving three different methods of OH removal or accountability (viz.: fast scavenging of OH; high system dilution with helium; admixture of excess H_2O_2 to achieve OH:HO_2 steady-state by promoting Reaction XXIX.46 ($OH + H_2O_2 \rightarrow HO_2 + H_2O$) as a counter-process to Reaction XXIX.38). When coupled with absolute species detection by laser magnetic resonance, of the order of $10^9(HO_2)cm^{-3}$ and $10^7(OH)cm^{-3}$, all three techniques yielded the same rate constant $k = (8\pm3) \times 10^{-12} cm^3 sec^{-1}$ (with unknown temperature dependence) which we now recommend.

bn - Pressure-dependent.

bo - For additional quenchants of $O(^1D)$, see Table 20-8 (Chp. 20).

bp - T_v-dependent rate coefficients have been calculated from the data of Ref. 24-111 for the reverse (excitation) reaction, by detailed-balance computation (Ref. 24-112) at each energy, and curve-fitting (by Handbook Editor) throughout the temperature range indicated.

bq - Cf. Figure 20-9 (Chp. 20).

br - For additional quenchants of $O_2(a^1\Delta g)$, see Table 20-6 (Chp. 20).

bs - Products may include $O(^1S)$ or $N(^2D)$ (Ref. 24-118).

bt - Endothermic by 39 cm^{-1} ($\sim$0.005 eV).

bu - Case of resonant vibrational energy exchange at T = 300 K.

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