ANL/FPP/TM-297
REVISED

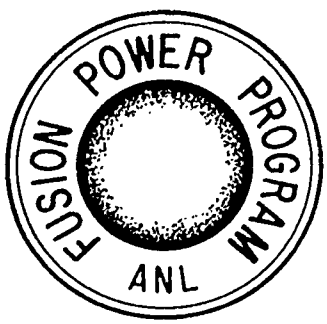
RECEIVED
OCT 13 1999
OSTI

HYDROCARBON RATE COEFFICIENTS FOR PROTON AND ELECTRON IMPACT IONIZATION, DISSOCIATION, AND RECOMBINATION IN A HYDROGEN PLASMA

by

J. N. Brooks, Z. Wang, D. N. Ruzic, and D. A. Alman

May 1999



FUSION POWER PROGRAM

Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

Operated by
The University of Chicago
for the U.S. Department of Energy
under Contract W-31-109-Eng-38

Argonne National Laboratory, with facilities in the states of Illinois and Idaho, is owned by the United States government, and operated by The University of Chicago under the provisions of a contract with the Department of Energy.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Reproduced from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831
Prices available from (423) 576-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Distribution Category:
Magnetic Fusion Reactor Materials

REVISED

ANL/FPP/TM-297

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

Hydrocarbon Rate Coefficients for Proton and Electron Impact Ionization, Dissociation, and Recombination in a Hydrogen Plasma

by

J. N. Brooks and Z. Wang
Fusion Power Program
Energy Technology Division
Argonne National Laboratory*

D.N. Ruzic and D.A. Alman
University of Illinois at Urbana/Champaign

May 1999

*ANL Work supported by the
Office of Fusion Energy
U.S. Department of Energy
Under Contract W-31-109-Eng-38

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	Page
Abstract	1
1. Introduction	1
2. Proton Impact Ionization-Rate Coefficients	2
3. Dissociative Recombination-Rate Coefficients	3
4. Electron Impact Ionization-Cross Sections	3
5. Electron Impact Dissociation-Cross Sections	3
6. Electron Impact Ionization and Dissociation-Rate Coefficients	4
Acknowledgments	4
References	4

LIST OF FIGURES

Figure No.		Page
1	e (-) + CH	17
2	e (-) + CH2	18
3	e (-) + CH3	19
4	e (-) + CH4	20
5	e (-) + C2H	21
6	e (-) + C2H2	22
7	e (-) + C2H3	23
8	e (-) + C2H4	24
9	e (-) + C2H5	25
10	e (-) + C2H6	26
11	e (-) + C3H	27
12	e (-) + C3H2	28
13	e (-) + C3H3	29
14	e (-) + C3H4	30
15	e (-) + C3H5	31
16	e (-) + C3H6	32

LIST OF TABLES

Table No.		Page
1	Proton impact ionization reaction rate coefficients	5
2	Dissociative recombination reaction rate coefficients	7
3	Electron impact ionization cross sections	8
4	Electron impact dissociation cross sections	13

Hydrocarbon Rate Coefficients for Proton and Electron Impact Ionization, Dissociation, and Recombination in a Hydrogen Plasma

J.N. Brooks, Z. Wang
Argonne National Laboratory
9700 South Cass Avenue, Argonne IL 60439

D.N. Ruzic, D.A. Alman
University of Illinois at Urbana Champaign
103 South Goodwin Avenue, Urbana IL 61801

Abstract

We estimate cross sections and rate coefficients for proton and electron impact ionization, dissociation, and recombination of neutral and ionized hydrocarbon molecules and fragments of the form $C_xH_y^k$, x = 1-3, y = 1-6, k = 0,1 in a thermalized hydrogen-electron plasma.

1. Introduction

The purpose of this work is to provide estimates of rate coefficients for use in calculations of hydrocarbon transport in a hydrogen isotope plasma. We developed these estimates for use in fusion applications, namely to study the transport of hydrocarbons chemically sputtered from a carbon plasma-facing surface. The rate coefficients are intended to be of reasonable "ballpark" accuracy, in keeping with the numerous uncertainties present anyway in most plasma-surface interaction calculations (e.g., plasma parameters, sputter yields, transport coefficients). With this limitation in mind it is noted that these rates may be useful for future fusion calculations and other calculations involving carbon/hydrogen plasmas.

Two of the reactions considered, i.e., proton impact ionization and dissociative recombination, are most important for fusion applications at so-called detached plasma

conditions, with electron temperatures of roughly 1-3 eV. These reactions and their application to chemical sputtering/hydrocarbon transport calculations are discussed in [1-3], and rate coefficient estimates from [1-3] are summarized here.

The second two reactions considered, electron impact ionization and electron impact dissociation, are not critical at low plasma temperatures but become more important at roughly > 3 eV. For these reactions we have estimated the cross sections and then computed the rate coefficients numerically as described below.

As discussed in [1,3] the accuracy of these estimated rates and cross sections, as checked against known data, was found to be quite good, specifically with most comparisons showing an error of within ± 35%. However, the available data is limited making a general accuracy estimate difficult.

2. Proton Impact Ionization–Rate Coefficients

The rate coefficients were estimated directly from molecular polarizability considerations as discussed in Ref [1-3]. These are listed in Table 1.

As discussed in [2], for our purposes in low-temperature fusion calculations, we have assumed that all reactions produce an even distribution of products, but the exact distribution is uncertain.

For other hydrogen isotopes, i.e. D or T, the rates in Table 1 can be scaled by multiplying by a factor equal to the square root of the ratio of the reduced mass of the reaction constituents for a protium plasma to the reduced mass for the isotopic plasma in question.

For example for the reaction $D^+ + CD_4$ the first rate in Table 1 should be multiplied by sqrt [(1x16)/(1+16)/(2x20)/(2+20)] = 0.719, yielding a rate of 2.99 x 10^{-9} cm^3/s.

3. Dissociative Recombination–Rate Coefficients

The rate coefficients were estimated directly by scaling of data/estimates at thermal energies, scaling from known methane reactions, as well as polarizability considerations, as discussed in Ref [1-3]. These are listed in Table 2 for electron temperature T.

Again, an even distribution of products has been assumed for fusion related calculations. This is believed to be a reasonable rough-estimate, but caution is urged regarding use in high-accuracy calculations.

4. Electron Impact Ionization–Cross Sections

We consider processes of the form:

$$e^- + C_xH_y \rightarrow C_xH_{y-j}^+ + jH + 2e^-$$

with j an integer depending on the specific reaction.

Cross sections for the reactions considered are shown in Table 3 as a function of electron energy.

5. Electron Impact Dissociation–Cross Sections

We consider processes of the form:

$$e^- + C_xH_y \rightarrow C_{x-n}H_{y-m} + nC + mH + e^-$$

with n,m integers depending on the specific reaction.

Cross sections for the reactions considered are shown in Table 4 as a function of electron energy.

6. Electron Impact Ionization and Dissociation–Rate Coefficients

The rate coefficient, for a Maxwellian plasma, is given by:

$$\langle \sigma v \rangle = (2 / kT)^{1.5} \sqrt{1 / \pi m_e} \int_0^\infty E \exp(-E / kT)\, \sigma(E) dE$$

for electron temperature T, cross section σ, electron mass m_e, and assuming negligible hydrocarbon speed compared to electron speed.

The rate coefficients for electron impact ionization and electron impact dissociation were computed numerically for electron temperatures of 1-2000 eV (via Simpson's rule with 1 eV energy intervals, and with energy integration range of 0-10,000 eV) using the above equation with the cross sections of Table 3 and 4 respectively.

Figures 1-16 show the computed rate coefficients (mks units), grouped by particle type.

Acknowledgments

University of Illinois work was supported by the U.S. Department of Energy and the National Science Foundation under DOE/NSF Grant # DE-FG02-97ER54440, DOE Grant # DE-FG02-99ER54515, and DOE/ANL Contract 980332401.

References

1. D.A. Alman, D.N. Ruzic, "A Model of Hydrocarbon Reactions in Low Temperature Hydrogen Plasmas," Physics of Plasmas, submitted.

2. J.N. Brooks, D. Alman, G. Federici, D.N. Ruzic, D.G. Whyte, "Erosion/redeposition analysis: status of modeling and code validation for semi-detached edge plasmas," Journal of Nuclear Materials, to be published (1999).

3. D.A. Alman, M. S. Thesis, University of Illinois (to be published).

Table 1. Proton impact ionization reaction rate coefficients

Reaction		Products	Total Rate Coeff. (cm^3/s)
$H^+ + CH_4$	$\rightarrow$	$0.5\ CH_4^+ + H$	4.15×10^{-9}
		$0.5\ CH_3^+ + H_2$	
$H^+ + CH_3$	$\rightarrow$	$0.5\ CH_3^+ + H$	3.6×10^{-9}
		$0.5\ CH_2^+ + H_2$	
$H^+ + CH_2$	$\rightarrow$	$0.5\ CH_2^+ + H$	3.4×10^{-9}
		$0.5\ CH^+ + H_2$	
$H^+ + CH$	$\rightarrow$	$1.0\ CH^+ + H$	3.2×10^{-9}
$H^+ + C_2H_6$	$\rightarrow$	$0.33\ C_2H_5^+ + H_2$	3.9×10^{-9}
		$0.33\ C_2H_4^+ + H_2 + H$	
		$0.33\ C_2H_3^+ + H_2 + H_2$	
$H^+ + C_2H_5$	$\rightarrow$	$0.33\ C_2H_5^+ + H$	4.9×10^{-9}
		$0.33\ C_2H_4^+ + H_2$	
		$0.33\ C_2H_3^+ + H_2 + H$	
$H^+ + C_2H_4$	$\rightarrow$	$0.33\ C_2H_4^+ + H$	5.0×10^{-9}
		$0.33\ C_2H_3^+ + H_2$	
		$0.33\ C_2H_2^+ + H_2 + H$	
$H^+ + C_2H_3$	$\rightarrow$	$0.33\ C_2H_3^+ + H$	4.6×10^{-9}
		$0.33\ C_2H_2^+ + H_2$	
		$0.33\ C_2H^+ + H_2 + H$	
$H^+ + C_2H_2$	$\rightarrow$	$0.5\ C_2H_2^+ + H$	6.3×10^{-9}
		$0.5\ C_2H^+ + H_2$	
$H^+ + C_2H$	$\rightarrow$	$1.00\ C_2H^+ + H$	4.4×10^{-9}
$H^+ + C_3H_6$	$\rightarrow$	$0.33\ C_3H_6^+ + H$	5.8×10^{-9}
		$0.33\ C_3H_5^+ + H_2$	
		$0.33\ C_3H_4^+ + H_2 + H$	
$H^+ + C_3H_5$	$\rightarrow$	$0.33\ C_3H_5^+ + H$	5.7×10^{-9}
		$0.33\ C_3H_4^+ + H_2$	
		$0.33\ C_3H_3^+ + H_2 + H$	

$H^+ + C_3H_4$	$\rightarrow$	0.33 $C_3H_4^+ + H$	5.9×10^{-9}
		0.33 $C_3H_3^+ + H_2$	
		0.33 $C_3H_2^+ + H_2 + H$	
$H^+ + C_3H_3$	$\rightarrow$	0.33 $C_3H_3^+ + H$	5.5×10^{-9}
		0.33 $C_3H_2^+ + H_2$	
		0.33 $C_3H^+ + H_2 + H$	
$H^+ + C_3H_2$	$\rightarrow$	0.5 $C_3H_2^+ + H$	5.4×10^{-9}
		0.5 $C_3H^+ + H_2$	
$H^+ + C_3H$	$\rightarrow$	1.0 $C_3H^+ + H$	5.2×10^{-9}

Table 2. Dissociative recombination reaction rate coefficients

Reaction		Products	Total Rate Coeff. (cm^3/s)	
$e^- + CH_4^+$	$\rightarrow$	$0.25\ CH_3 + H$	$5.4\times10^{-8}T^{-0.84}$	T <1 eV
		$0.75\ CH_2 + H_2$	$5.4\times10^{-8}T^{-1.05}$	T >1 eV
$e^- + CH_3^+$	$\rightarrow$	$1.00\ CH_2 + H$	$6.8\times10^{-8}T^{-0.770}$	T <1 eV
			$6.8\times10^{-8}T^{-0.979}$	T >1 eV
$e^- + CH_2^+$	$\rightarrow$	$1.00\ CH + H$	$1.0\times10^{-7}T^{-0.544}$	T <1 eV
			$1.0\times10^{-7}T^{-1.21}$	T >1 eV
$e^- + CH^+$	$\rightarrow$	$1.00\ C + H$	$7.0\times10^{-8}T^{-0.553}$	T <1 eV
			$7.0\times10^{-8}T^{-1.18}$	T >1 eV
$e^- + C_2H_6^+$	$\rightarrow$	$0.50\ C_2H_5 + H$	$9.9\times10^{-8}T^{-0.50}$	
		$0.50\ C_2H_4 + H_2$		
$e^- + C_2H_5^+$	$\rightarrow$	$0.50\ C_2H_4 + H$	$9.65\times10^{-8}T^{-0.50}$	
		$0.50\ C_2H_3 + H_2$		
$e^- + C_2H_4^+$	$\rightarrow$	$0.50\ C_2H_3 + H$	$1.00\times10^{-7}T^{-0.50}$	
		$0.50\ C_2H_2 + H_2$		
$e^- + C_2H_3^+$	$\rightarrow$	$0.50\ C_2H_2 + H$	$1.10\times10^{-7}T^{-0.50}$	
		$0.50\ C_2H + H_2$		
$e^- + C_2H_2^+$	$\rightarrow$	$0.33\ C_2H + H$	$6.81\times10^{-8}T^{-0.50}$	
		$0.33\ CH + CH$		
		$0.33\ C + C + H + H$		
$e^- + C_2H^+$	$\rightarrow$	$0.50\ C + C + H$	$9.28\times10^{-8}T^{-0.50}$	
		$0.50\ CH + C$		
$e^- + C_3H_6^+$	$\rightarrow$	$0.50\ C_3H_5 + H$	$5.50\times10^{-8}T^{-0.50}$	
		$0.50\ C_3H_4 + H_2$		
$e^- + C_3H_5^+$	$\rightarrow$	$0.50\ C_3H_4 + H$	$5.63\times10^{-8}T^{-0.50}$	
		$0.50\ C_3H_3 + H_2$		
$e^- + C_3H_4^+$	$\rightarrow$	$0.50\ C_3H_3 + H$	$1.10\times10^{-7}T^{-0.50}$	
		$0.50\ C_3H_2 + H_2$		
$e^- + C_3H_3^+$	$\rightarrow$	$0.50\ C_3H_2 + H$	$1.10\times10^{-7}T^{-0.50}$	
		$0.50\ C_3H + H_2$		
$e^- + C_3H_2^+$	$\rightarrow$	$0.50\ C_2H + CH$	$1.10\times10^{-7}T^{-0.50}$	
		$0.50\ C_3H + H$		
$e^- + C_3H^+$	$\rightarrow$	$0.33\ CH + C + C$	$1.10\times10^{-7}T^{-0.50}$	
		$0.33\ C_2H + C$		
		$0.33\ C + C + C + H$		

Table 3. Electron impact ionization cross sections

Reaction		Cross Section (cm^2) †	Energy Range (eV)
$e^- + CH_4$	$\rightarrow CH_4^+ + 2e^-$	$1.8\times10^{-16}\left[1-\left(\frac{90-E}{90-12.6}\right)^2\right]$	$12.6<E<90$
		$1.8\times10^{-16}\exp\left[\frac{90-E}{748}\right]$	$E>90$
	$\rightarrow CH_3^+ + H + 2e^-$	$1.4\times10^{-16}\left[1-\left(\frac{100-E}{100-14.3}\right)^2\right]$	$14.3<E<100$
		$1.4\times10^{-16}\exp\left[\frac{100-E}{799}\right]$	$E>100$
$e^- + CH_3$	$\rightarrow CH_3^+ + 2e^-$	$1.8\times10^{-16}\left[1-\left(\frac{95-E}{95-12.6}\right)^2\right]$	$12.6<E<95$
		$1.8\times10^{-16}\exp\left[\frac{95-E}{767}\right]$	$E>95$
	$\rightarrow CH_2^+ + H + 2e^-$	$1.0\times10^{-16}\left[1-\left(\frac{85-E}{85-15}\right)^2\right]$	$15<E<85$
		$1.0\times10^{-16}\exp\left[\frac{85-E}{832}\right]$	$E>85$
$e^- + CH_2$	$\rightarrow CH_2^+ + 2e^-$	$1.8\times10^{-16}\left[1-\left(\frac{95-E}{95-12.6}\right)^2\right]$	$12.6<E<95$
		$1.8\times10^{-16}\exp\left[\frac{95-E}{767}\right]$	$E>95$
	$\rightarrow CH^+ + H + 2e^-$	$6.5\times10^{-17}\left[1-\left(\frac{95-E}{95-17.9}\right)^2\right]$	$17.9<E<95$
		$6.5\times10^{-17}\exp\left[\frac{95-E}{800}\right]$	$E>95$
$e^- + CH$	$\rightarrow CH^+ + 2e^-$	$1.8\times10^{-16}\left[1-\left(\frac{95-E}{95-12.6}\right)^2\right]$	$12.6<E<95$
		$1.8\times10^{-16}\exp\left[\frac{95-E}{746}\right]$	$E>95$
	$\rightarrow C^+ + H + 2e^-$	$3.1\times10^{-17}\left[1-\left(\frac{95-E}{95-17}\right)^2\right]$	$17<E<95$

		$3.1\times10^{-17}\exp\left[\frac{95-E}{816}\right]$	$E>95$
$e^- + C_2H_6$	$\rightarrow C_2H_6^+ + 2e^-$	$1.32\times10^{-16}\left[1-\left(\frac{86-E}{86-10}\right)^2\right]$	$10<E<86$
		$1.32\times10^{-16}\exp\left[\frac{86-E}{742}\right]$	$E>86$
	$\rightarrow C_2H_5^+ + H + 2e^-$	$8.66\times10^{-17}\left[1-\left(\frac{86-E}{86-12}\right)^2\right]$	$12<E<86$
		$8.66\times10^{-17}\exp\left[\frac{86-E}{742}\right]$	$E>86$
	$\rightarrow C_2H_4^+ + H_2 + 2e^-$	$4.37\times10^{-16}\left[1-\left(\frac{86-E}{86-12}\right)^2\right]$	$12<E<86$
		$4.37\times10^{-16}\exp\left[\frac{86-E}{742}\right]$	$E>86$
$e^- + C_2H_5$	$\rightarrow C_2H_5^+ + 2e^-$	$1.24\times10^{-16}\left[1-\left(\frac{89-E}{89-10}\right)^2\right]$	$10<E<89$
		$1.24\times10^{-16}\exp\left[\frac{89-E}{717}\right]$	$E>89$
	$\rightarrow C_2H_4^+ + H + 2e^-$	$8.11\times10^{-17}\left[1-\left(\frac{89-E}{89-12}\right)^2\right]$	$12<E<89$
		$8.11\times10^{-17}\exp\left[\frac{89-E}{717}\right]$	$E>89$
	$\rightarrow C_2H_3^+ + H_2 + 2e^-$	$4.10\times10^{-16}\left[1-\left(\frac{89-E}{89-12}\right)^2\right]$	$12<E<89$
		$4.10\times10^{-16}\exp\left[\frac{89-E}{717}\right]$	$E>89$
$e^- + C_2H_4$	$\rightarrow C_2H_4^+ + 2e^-$	$1.15\times10^{-16}\left[1-\left(\frac{90-E}{90-10}\right)^2\right]$	$10<E<90$
		$1.15\times10^{-16}\exp\left[\frac{90-E}{668}\right]$	$E>90$
	$\rightarrow C_2H_3^+ + H + 2e^-$	$7.57\times10^{-17}\left[1-\left(\frac{90-E}{90-12}\right)^2\right]$	$12<E<90$
		$7.57\times10^{-17}\exp\left[\frac{90-E}{668}\right]$	$E>90$

	$\rightarrow C_2H_2^+ + H_2 + 2e^-$	$3.82\times10^{-16}\left[1-\left(\frac{90-E}{90-12}\right)^2\right]$	$12<E<90$
		$3.82\times10^{-16}\exp\left[\frac{90-E}{668}\right]$	$E>90$
$e^- + C_2H_3$	$\rightarrow C_2H_3^+ + 2e^-$	$1.07\times10^{-16}\left[1-\left(\frac{86-E}{86-10}\right)^2\right]$	$10<E<86$
		$1.07\times10^{-16}\exp\left[\frac{86-E}{646}\right]$	$E>86$
	$\rightarrow C_2H_2^+ + H + 2e^-$	$7.02\times10^{-17}\left[1-\left(\frac{86-E}{86-12}\right)^2\right]$	$12<E<86$
		$7.02\times10^{-17}\exp\left[\frac{86-E}{646}\right]$	$E>86$
	$\rightarrow C_2H^+ + H_2 + 2e^-$	$3.55\times10^{-16}\left[1-\left(\frac{86-E}{86-12}\right)^2\right]$	$12<E<86$
		$3.55\times10^{-16}\exp\left[\frac{86-E}{646}\right]$	$E>86$
$e^- + C_2H_2$	$\rightarrow C_2H_2^+ + 2e^-$	$2.96\times10^{-16}\left[1-\left(\frac{87-E}{87-10}\right)^2\right]$	$12<E<87$
		$2.96\times10^{-16}\exp\left[\frac{87-E}{634}\right]$	$E>87$
	$\rightarrow C_2H^+ + H + 2e^-$	$1.94\times10^{-16}\left[1-\left(\frac{87-E}{87-12}\right)^2\right]$	$12<E<87$
		$1.94\times10^{-16}\exp\left[\frac{87-E}{634}\right]$	$E>87$
$e^- + C_2H$	$\rightarrow C_2H^+ + 2e^-$	$2.71\times10^{-16}\left[1-\left(\frac{84-E}{84-10}\right)^2\right]$	$10<E<84$
		$2.71\times10^{-16}\exp\left[\frac{84-E}{575}\right]$	$E>84$
	$\rightarrow C^+ + C + H + 2e^-$	$1.94\times10^{-16}\left[1-\left(\frac{84-E}{84-12}\right)^2\right]$	$12<E<84$
		$1.94\times10^{-16}\exp\left[\frac{84-E}{575}\right]$	$E>84$

$e^- + C_3H_6$	$\rightarrow C_3H_6^+ + 2e^-$	$1.79\times10^{-16}\left[1-\left(\frac{98-E}{98-10}\right)^2\right]$	$10<E<98$
		$1.79\times10^{-16}\exp\left[\frac{98-E}{688}\right]$	$E>98$
	$\rightarrow C_3H_5^+ + H + 2e^-$	$1.18\times10^{-16}\left[1-\left(\frac{98-E}{98-12}\right)^2\right]$	$12<E<98$
		$1.18\times10^{-16}\exp\left[\frac{98-E}{688}\right]$	$E>98$
	$\rightarrow C_3H_4^+ + 2H + 2e^-$	$5.95\times10^{-16}\left[1-\left(\frac{98-E}{98-12}\right)^2\right]$	$12<E<98$
		$5.95\times10^{-16}\exp\left[\frac{98-E}{688}\right]$	$E>98$
$e^- + C_3H_5$	$\rightarrow C_3H_5^+ + 2e^-$	$1.71\times10^{-16}\left[1-\left(\frac{97-E}{97-10}\right)^2\right]$	$10<E<97$
		$1.71\times10^{-16}\exp\left[\frac{97-E}{652}\right]$	$E>97$
	$\rightarrow C_3H_4^+ + H + 2e^-$	$1.21\times10^{-16}\left[1-\left(\frac{97-E}{97-12}\right)^2\right]$	$12<E<97$
		$1.21\times10^{-16}\exp\left[\frac{97-E}{652}\right]$	$E>97$
	$\rightarrow C_3H_3^+ + 2H + 2e^-$	$5.67\times10^{-16}\left[1-\left(\frac{97-E}{97-12}\right)^2\right]$	$12<E<97$
		$5.67\times10^{-16}\exp\left[\frac{97-E}{652}\right]$	$E>97$
$e^- + C_3H_4$	$\rightarrow C_3H_4^+ + 2e^-$	$1.63\times10^{-16}\left[1-\left(\frac{95-E}{95-10}\right)^2\right]$	$10<E<95$
		$1.63\times10^{-16}\exp\left[\frac{95-E}{617}\right]$	$E>95$
	$\rightarrow C_3H_3^+ + H + 2e^-$	$1.07\times10^{-16}\left[1-\left(\frac{95-E}{95-12}\right)^2\right]$	$12<E<95$
		$1.07\times10^{-16}\exp\left[\frac{95-E}{617}\right]$	$E>95$

	$\rightarrow C_3H_2^+ + 2H + 2e^-$	$5.40\times10^{-16}\left[1-\left(\frac{95-E}{95-12}\right)^2\right]$	$12<E<95$
		$5.40\times10^{-16}\exp\left[\frac{95-E}{617}\right]$	$E>95$
$e^- + C_3H_3$	$\rightarrow C_3H_3^+ + 2e^-$	$1.54\times10^{-16}\left[1-\left(\frac{94-E}{94-10}\right)^2\right]$	$10<E<94$
		$1.54\times10^{-16}\exp\left[\frac{94-E}{581}\right]$	$E>94$
	$\rightarrow C_3H_2^+ + H + 2e^-$	$1.01\times10^{-16}\left[1-\left(\frac{94-E}{94-12}\right)^2\right]$	$12<E<94$
		$1.01\times10^{-16}\exp\left[\frac{94-E}{581}\right]$	$E>94$
	$\rightarrow C_3H^+ + 2H + 2e^-$	$5.12\times10^{-16}\left[1-\left(\frac{94-E}{94-12}\right)^2\right]$	$12<E<94$
		$5.12\times10^{-16}\exp\left[\frac{94-E}{581}\right]$	$E>94$
$e^- + C_3H_2$	$\rightarrow C_3H_2^+ + 2e^-$	$4.39\times10^{-16}\left[1-\left(\frac{93-E}{93-10}\right)^2\right]$	$10<E<93$
		$4.39\times10^{-16}\exp\left[\frac{93-E}{546}\right]$	$E>93$
	$\rightarrow C_3H^+ + H + 2e^-$	$2.88\times10^{-16}\left[1-\left(\frac{93-E}{93-12}\right)^2\right]$	$12<E<93$
		$2.88\times10^{-16}\exp\left[\frac{93-E}{546}\right]$	$E>93$
$e^- + C_3H$	$\rightarrow C_3H^+ + 2e^-$	$6.85\times10^{-16}\left[1-\left(\frac{91-E}{91-10}\right)^2\right]$	$10<E<91$
		$6.85\times10^{-16}\exp\left[\frac{91-E}{511}\right]$	$E>91$

† Please note: All cross sections are zero below the threshold energy.

Table 4. Electron impact dissociation cross sections

Reaction		Cross Section (cm^2) †	Energy Range (eV)
$e^- + CH_4$	$\rightarrow CH_3 + H + e^-$	$1.4\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
		$1.4\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$
	$\rightarrow CH_2 + 2H + e^-$	$7.3\times10^{-17}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
		$7.3\times10^{-17}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^- + CH_3$	$\rightarrow CH_2 + H + e^-$	$1.27\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
		$1.27\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$
	$\rightarrow CH + 2H + e^-$	$6.33\times10^{-17}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
		$6.33\times10^{-17}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^- + CH_2$	$\rightarrow CH + H + e^-$	$7.33\times10^{-17}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
		$7.33\times10^{-17}\exp\left[\frac{25-E}{77}\right]$	$E>25$
	$\rightarrow C + 2H + e^-$	$3.67\times10^{-17}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
		$3.67\times10^{-17}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^- + CH$	$\rightarrow C + H + e^-$	$6.0\times10^{-17}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
		$6.0\times10^{-17}\exp\left[\frac{25-E}{77}\right]$	$E>25$
$e^- + C_2H_6$	$\rightarrow C_2H_5 + H + e^-$	$3.34\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$

		$3.34\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$
	$\rightarrow C_2H_4+2H+e^-$	$1.67\times10^{-16}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
		$1.67\times10^{-16}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^-+C_2H_5$	$\rightarrow C_2H_4+H+e^-$	$3.28\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
		$3.28\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$
	$\rightarrow C_2H_3+2H+e^-$	$1.64\times10^{-16}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
		$1.64\times10^{-16}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^-+C_2H_4$	$\rightarrow C_2H_3+H+e^-$	$3.13\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
		$3.13\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$
	$\rightarrow C_2H_2+2H+e^-$	$1.56\times10^{-16}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
		$1.56\times10^{-16}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^-+C_2H_3$	$\rightarrow C_2H_2+H+e^-$	$2.84\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
		$2.84\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$
	$\rightarrow C_2H+2H+e^-$	$1.42\times10^{-16}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
		$1.42\times10^{-16}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^-+C_2H_2$	$\rightarrow C_2H+H+e^-$	$4.06\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
		$4.06\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$

$e^- + C_2H \rightarrow C + C + H + e^-$	$3.60\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
	$3.60\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$
$e^- + C_3H_6 \rightarrow C_3H_5 + H + e^-$	$4.76\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
	$4.76\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$
$\rightarrow C_3H_4 + 2H + e^-$	$2.38\times10^{-16}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
	$2.38\times10^{-16}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^- + C_3H_5 \rightarrow C_3H_4 + H + e^-$	$4.53\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
	$4.53\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>77$
$\rightarrow C_3H_3 + 2H + e^-$	$2.27\times10^{-16}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
	$2.27\times10^{-16}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^- + C_3H_4 \rightarrow C_3H_3 + H + e^-$	$4.31\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
	$4.31\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$
$\rightarrow C_3H_2 + 2H + e^-$	$2.16\times10^{-16}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
	$2.16\times10^{-16}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^- + C_3H_3 \rightarrow C_3H_2 + H + e^-$	$4.10\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
	$4.10\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$

	$\rightarrow C_3H + 2H + e^-$	$2.05\times10^{-16}\left[1-\left(\frac{18-E}{18-10}\right)^2\right]$	$10<E<18$
		$2.05\times10^{-16}\exp\left[\frac{18-E}{11.4}\right]$	$E>18$
$e^- + C_3H_2$	$\rightarrow C_3H + H + e^-$	$5.82\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
		$5.82\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$
$e^- + C_3H$	$\rightarrow 3C + H + e^-$	$5.48\times10^{-16}\left[1-\left(\frac{25-E}{25-10}\right)^2\right]$	$10<E<25$
		$5.48\times10^{-16}\exp\left[\frac{25-E}{77}\right]$	$E>25$

† Please note: All cross sections are zero below the threshold energy.

Fig. 1

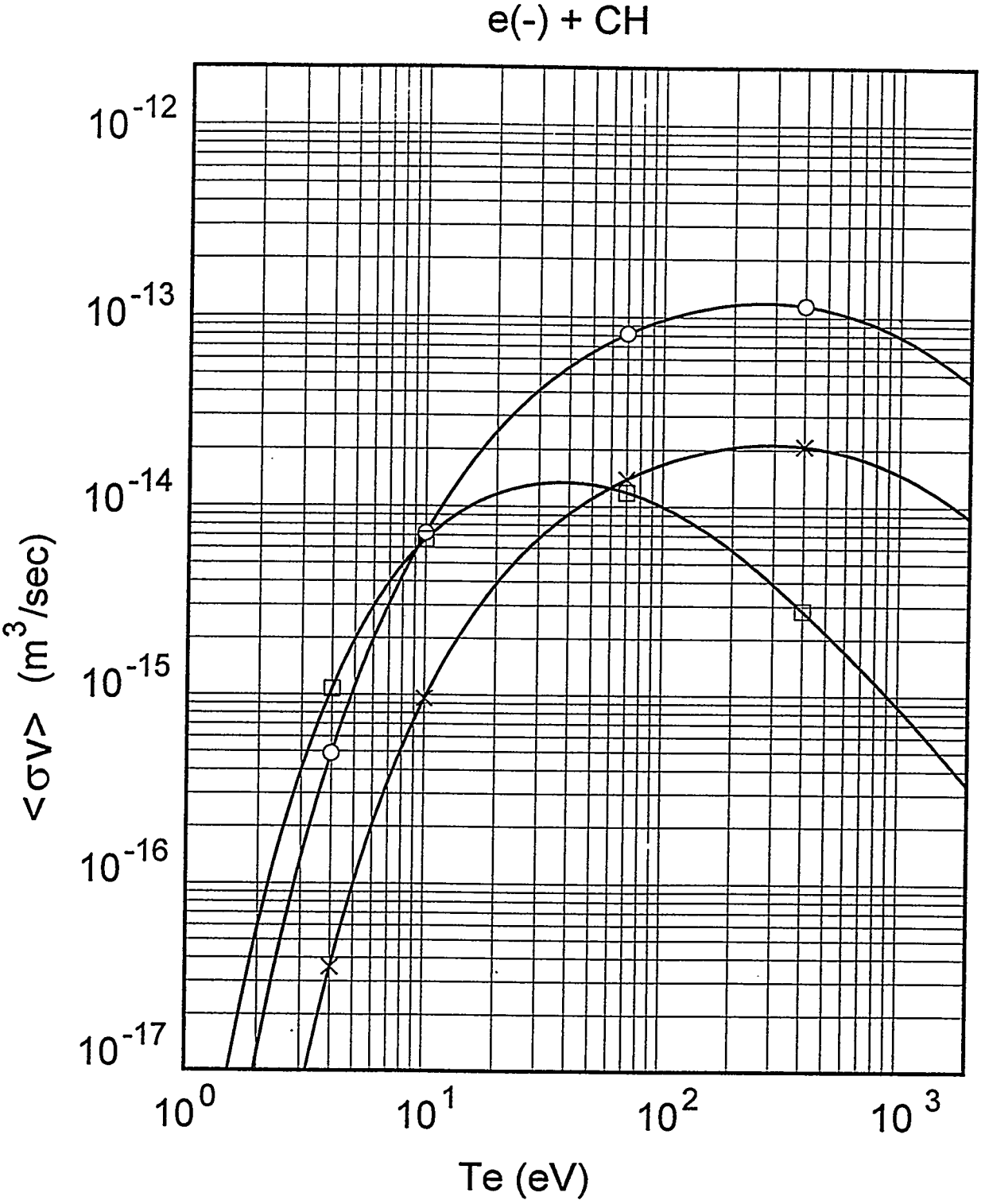

e(-) + CH
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
o e(-) + CH -> CH(+) + 2e(-)
× e(-) + CH -> C(+) + H + 2e(-)
□ e(-) + CH -> C + H + e(-)

Fig. 2

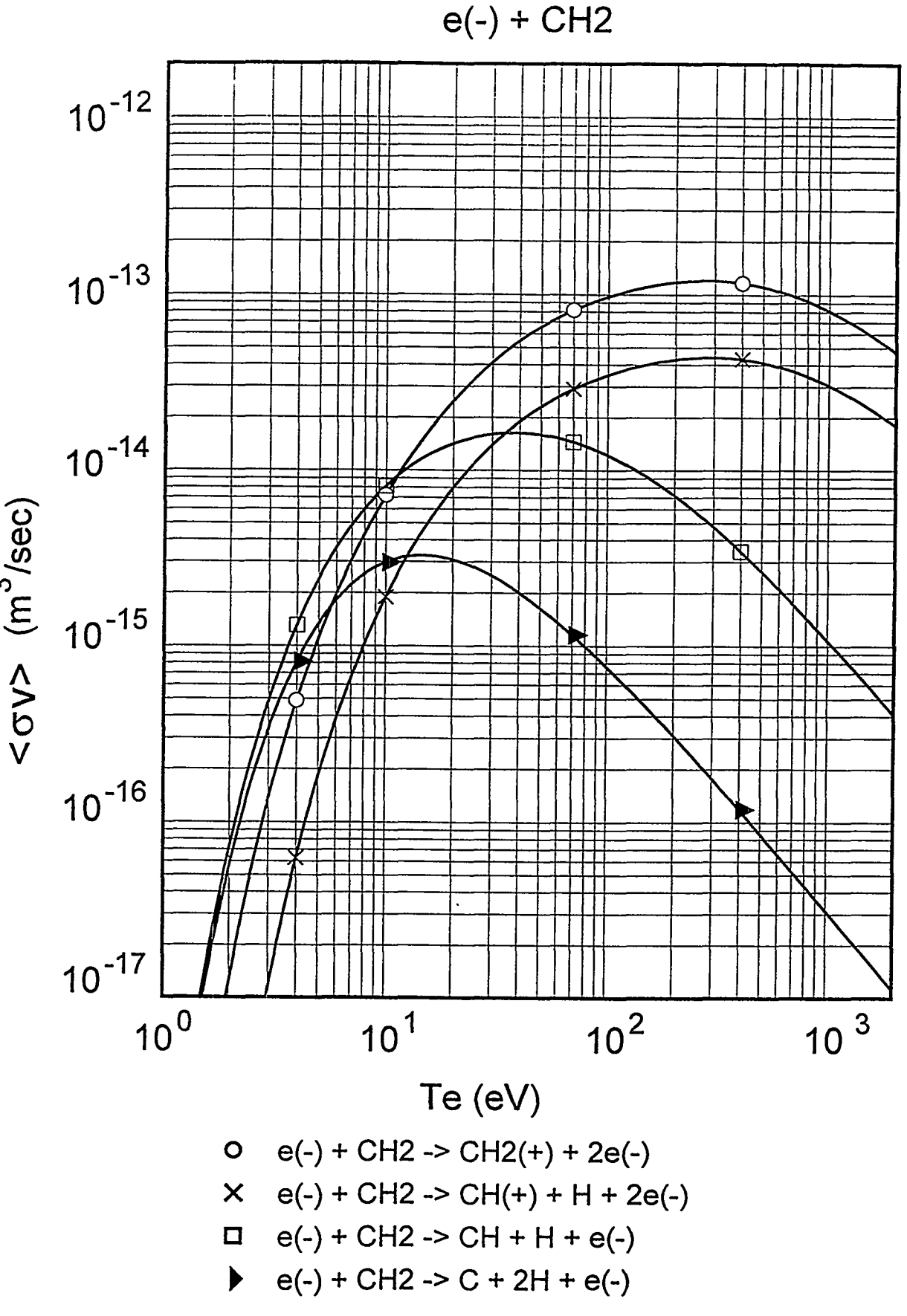

e(-) + CH2
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
e(-) + CH2 -> CH2(+) + 2e(-)
e(-) + CH2 -> CH(+) + H + 2e(-)
e(-) + CH2 -> CH + H + e(-)
e(-) + CH2 -> C + 2H + e(-)

Fig. 3

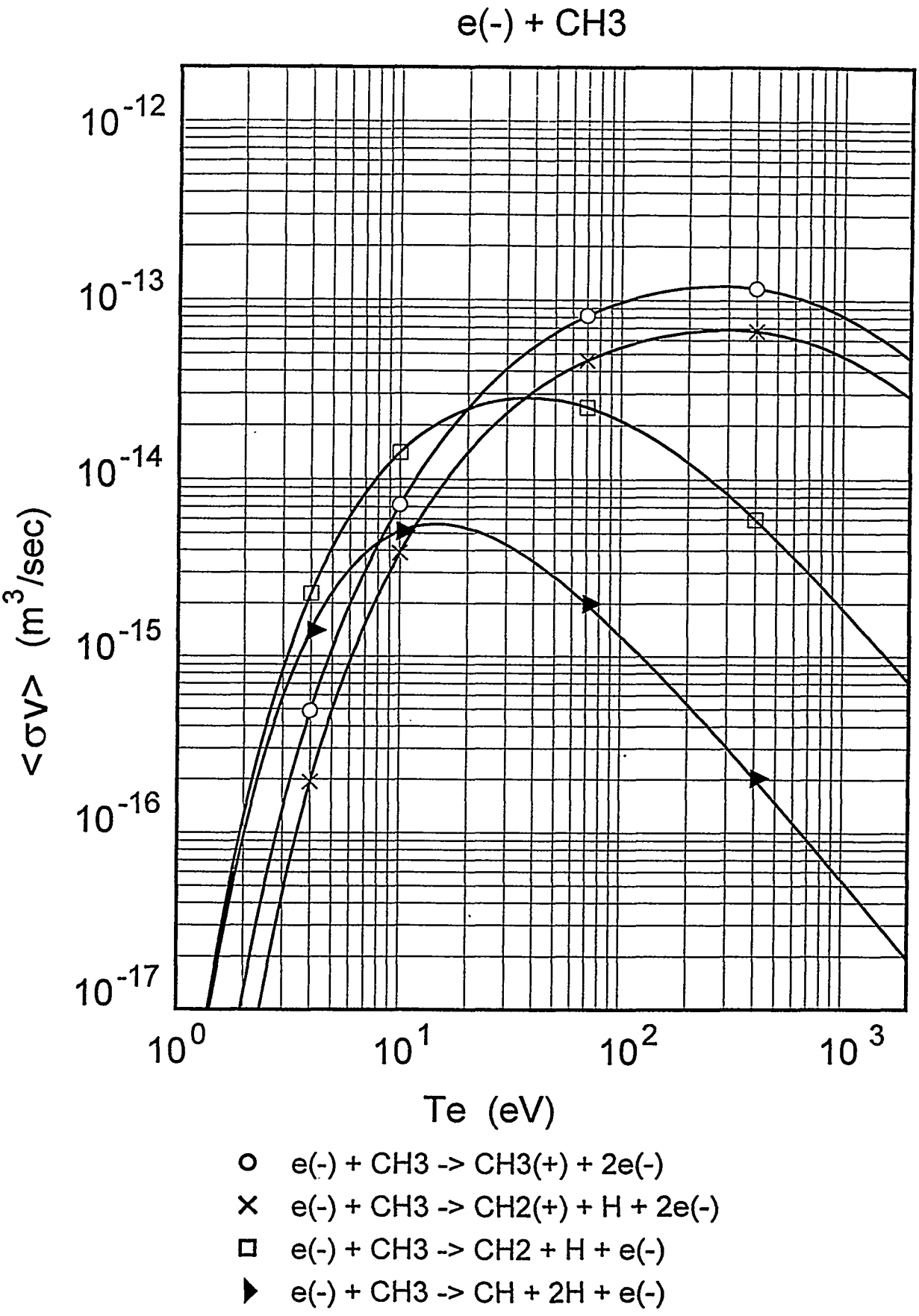

e(-) + CH3
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
e(-) + CH3 -> CH3(+) + 2e(-)
e(-) + CH3 -> CH2(+) + H + 2e(-)
e(-) + CH3 -> CH2 + H + e(-)
e(-) + CH3 -> CH + 2H + e(-)

Fig. 4

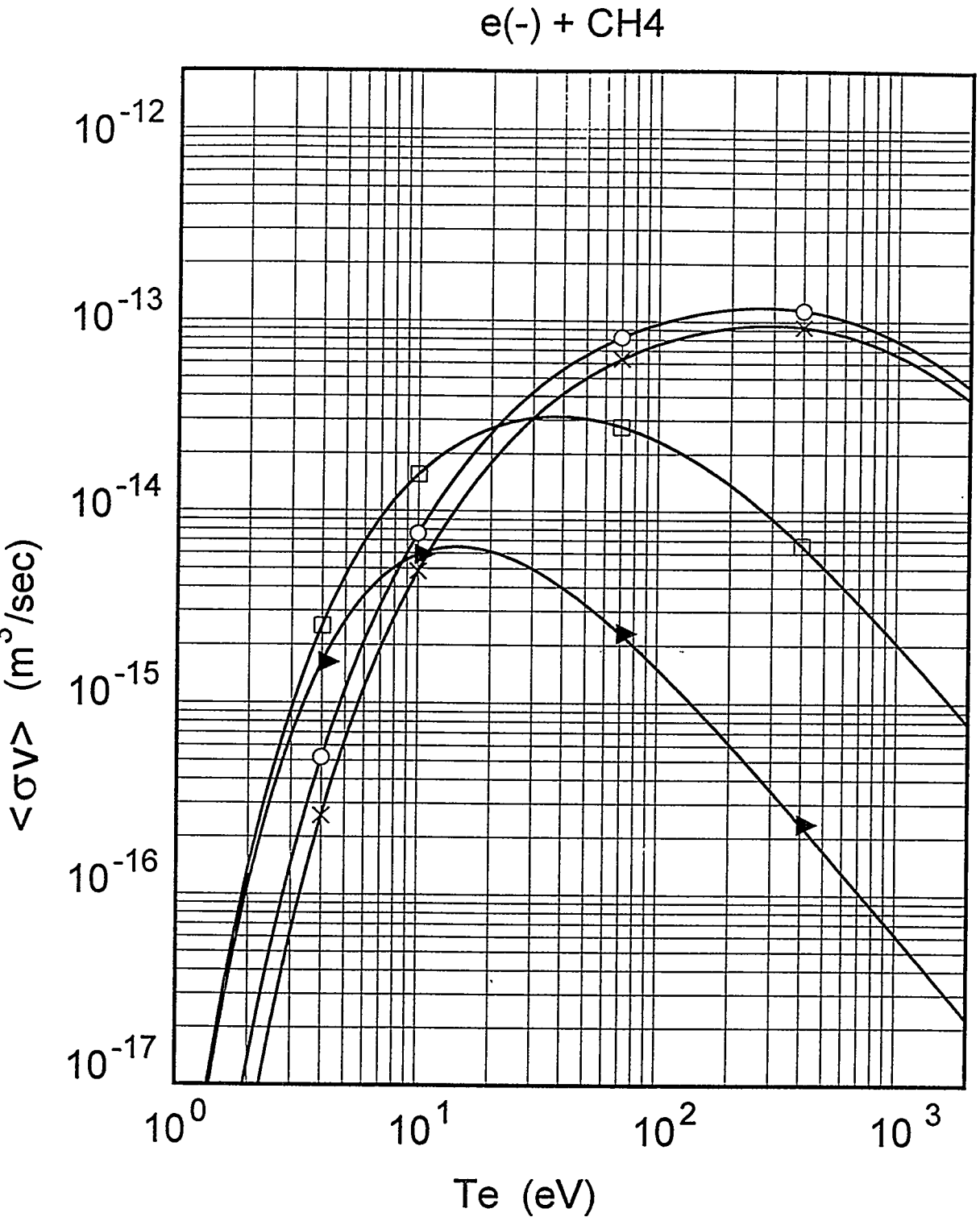

e(-) + CH4
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m^3/sec)
10^0
10^1
10^2
10^3
Te (eV)
e(-) + CH4 -> CH4(+) + 2e(-)
e(-) + CH4 -> CH3(+) + H + 2e(-)
e(-) + CH4 -> CH3 + H + e(-)
e(-) + CH4 -> CH2 + 2H + e(-)

Fig. 5

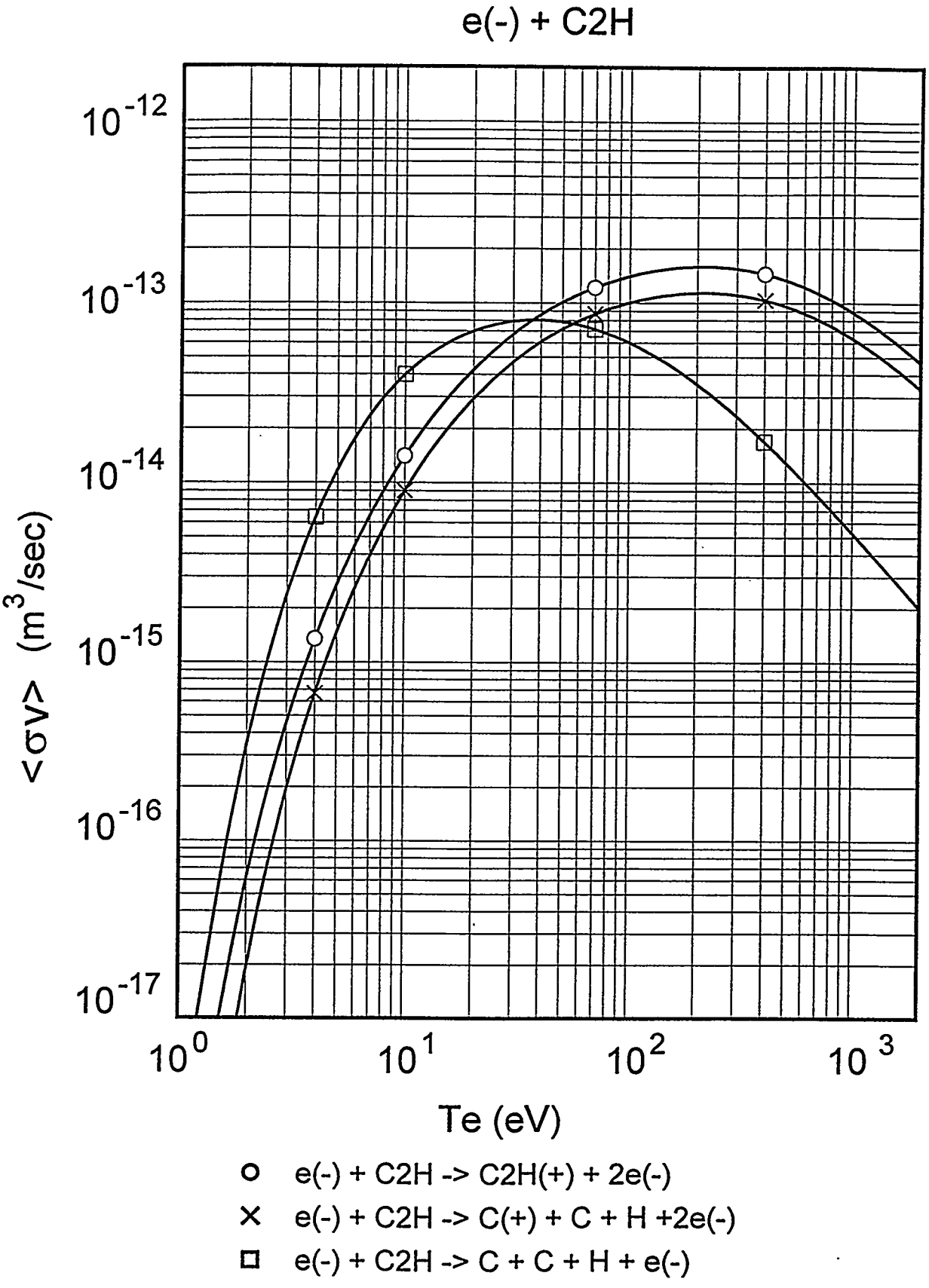

e(-) + C2H
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
o e(-) + C2H -> C2H(+) + 2e(-)
× e(-) + C2H -> C(+) + C + H +2e(-)
□ e(-) + C2H -> C + C + H + e(-)

Fig. 6

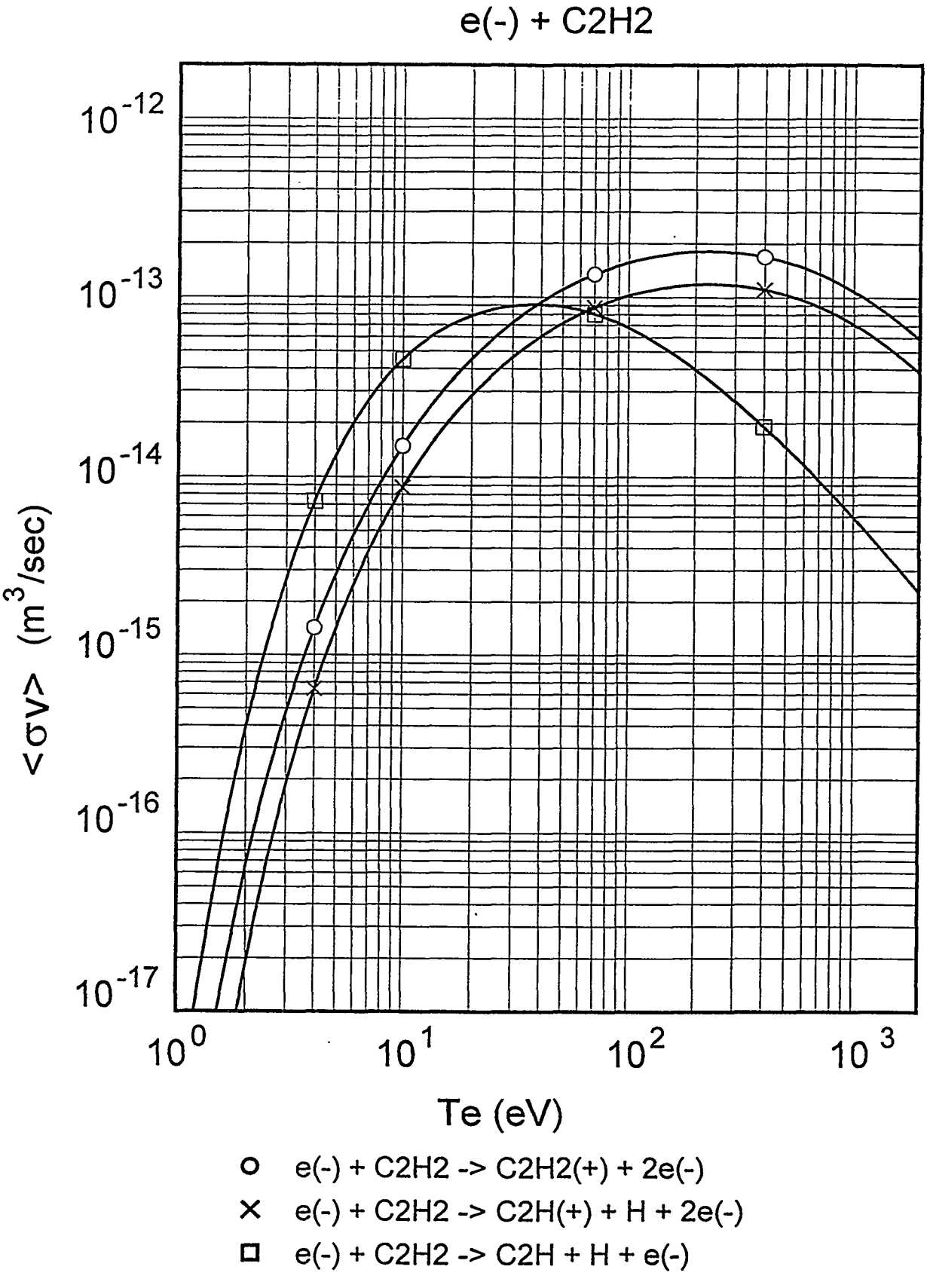

e(-) + C2H2
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
o e(-) + C2H2 -> C2H2(+) + 2e(-)
× e(-) + C2H2 -> C2H(+) + H + 2e(-)
□ e(-) + C2H2 -> C2H + H + e(-)

Fig. 7

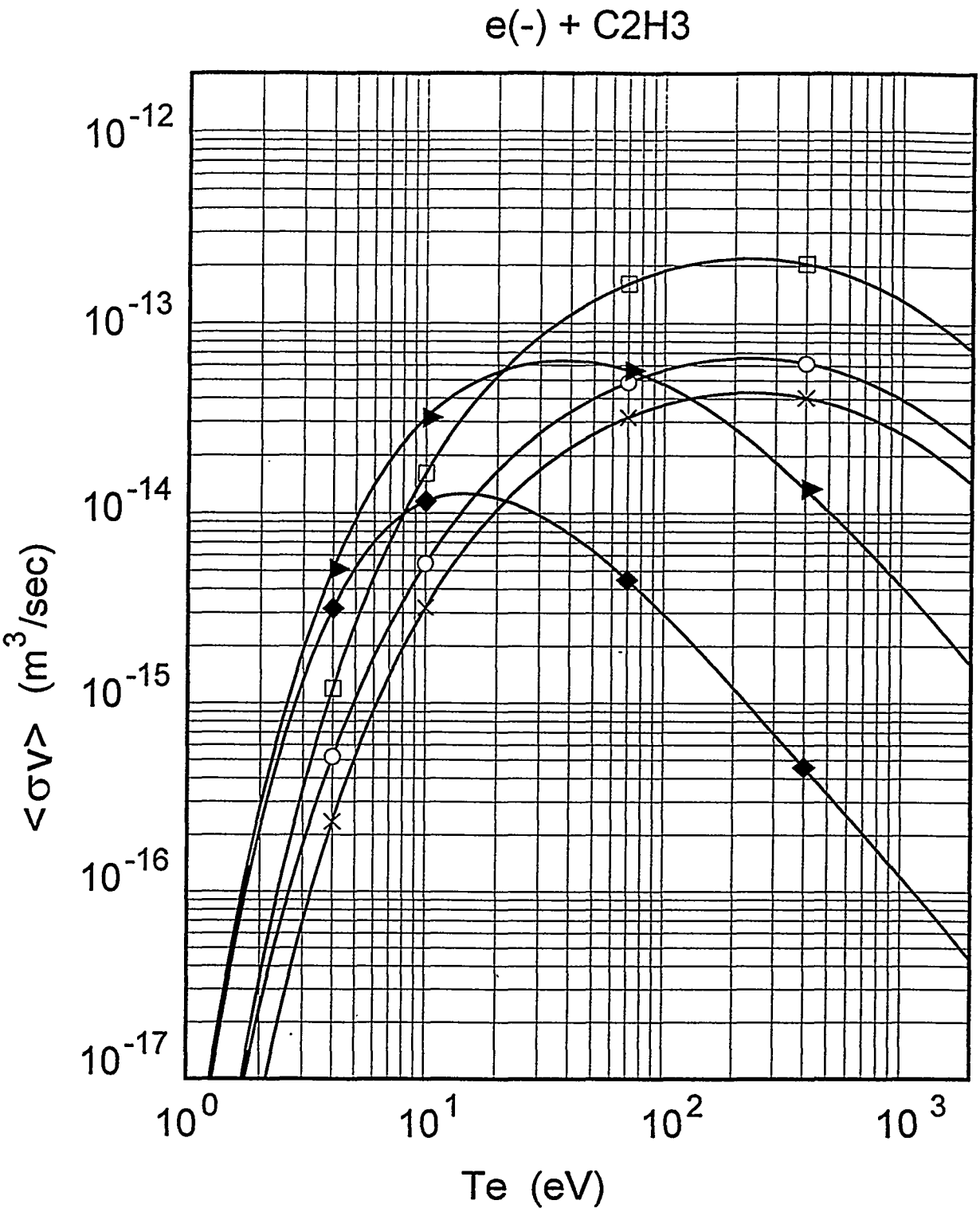

e(-) + C2H3
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
<σV> (m^3/sec)
10^0
10^1
10^2
10^3
Te (eV)
e(-) + C2H3 -> C2H3(+) + 2e(-)
e(-) + C2H3 -> C2H2(+) + H + 2e(-)
e(-) + C2H3 -> C2H(+) + 2H + 2e(-)
e(-) + C2H3 -> C2H2 + H + e(-)
e(-) + C2H3 -> C2H + 2H + e(-)

Fig. 8

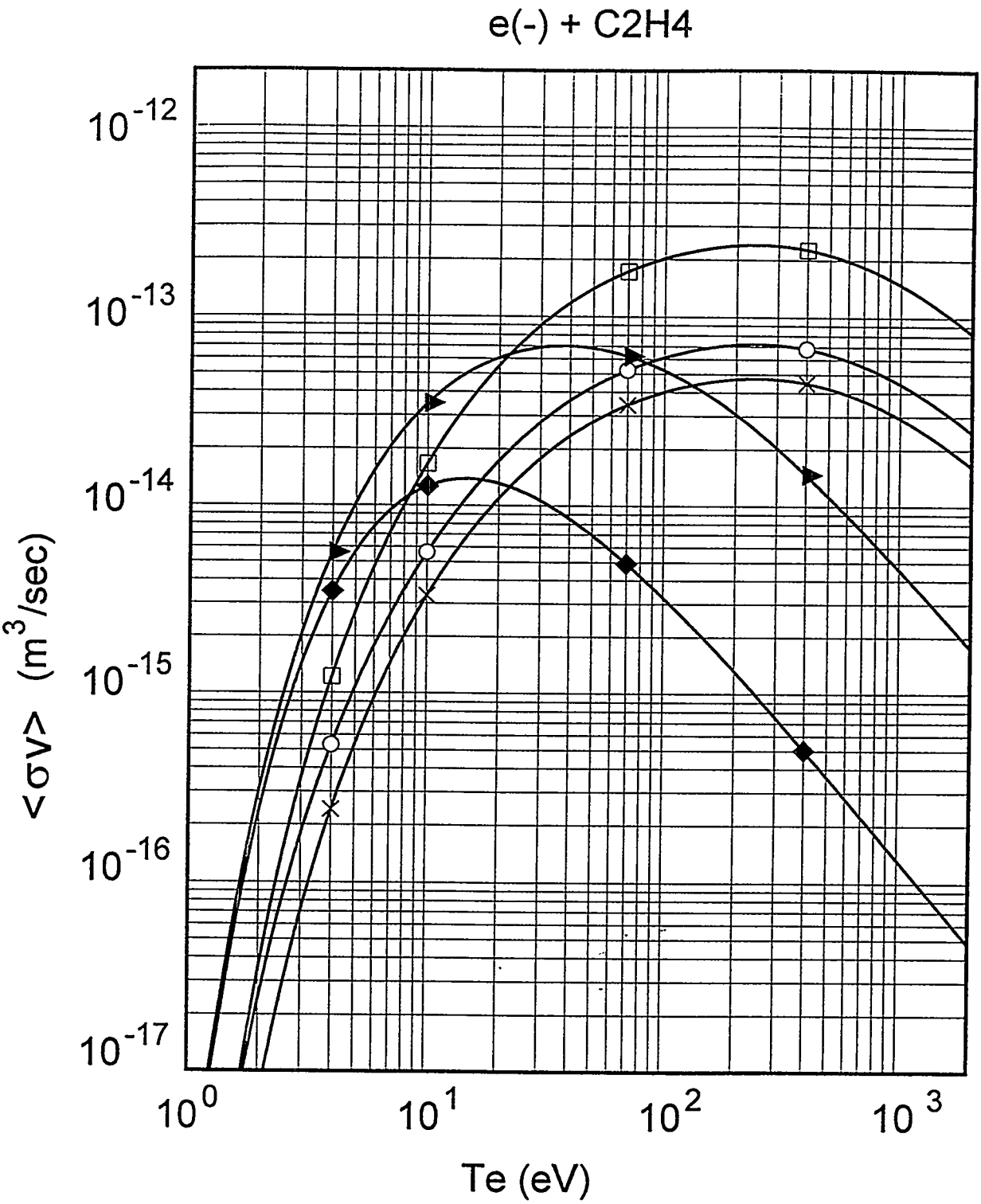

e(-) + C2H4
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
e(-) + C2H4 -> C2H4(+) + 2e(-)
e(-) + C2H4 -> C2H3(+) + H + 2e(-)
e(-) + C2H4 -> C2H2(+) + 2H + 2e(-)
e(-) + C2H4 -> C2H3 + H + e(-)
e(-) + C2H4 -> C2H2 + 2H + e(-)

Fig. 9

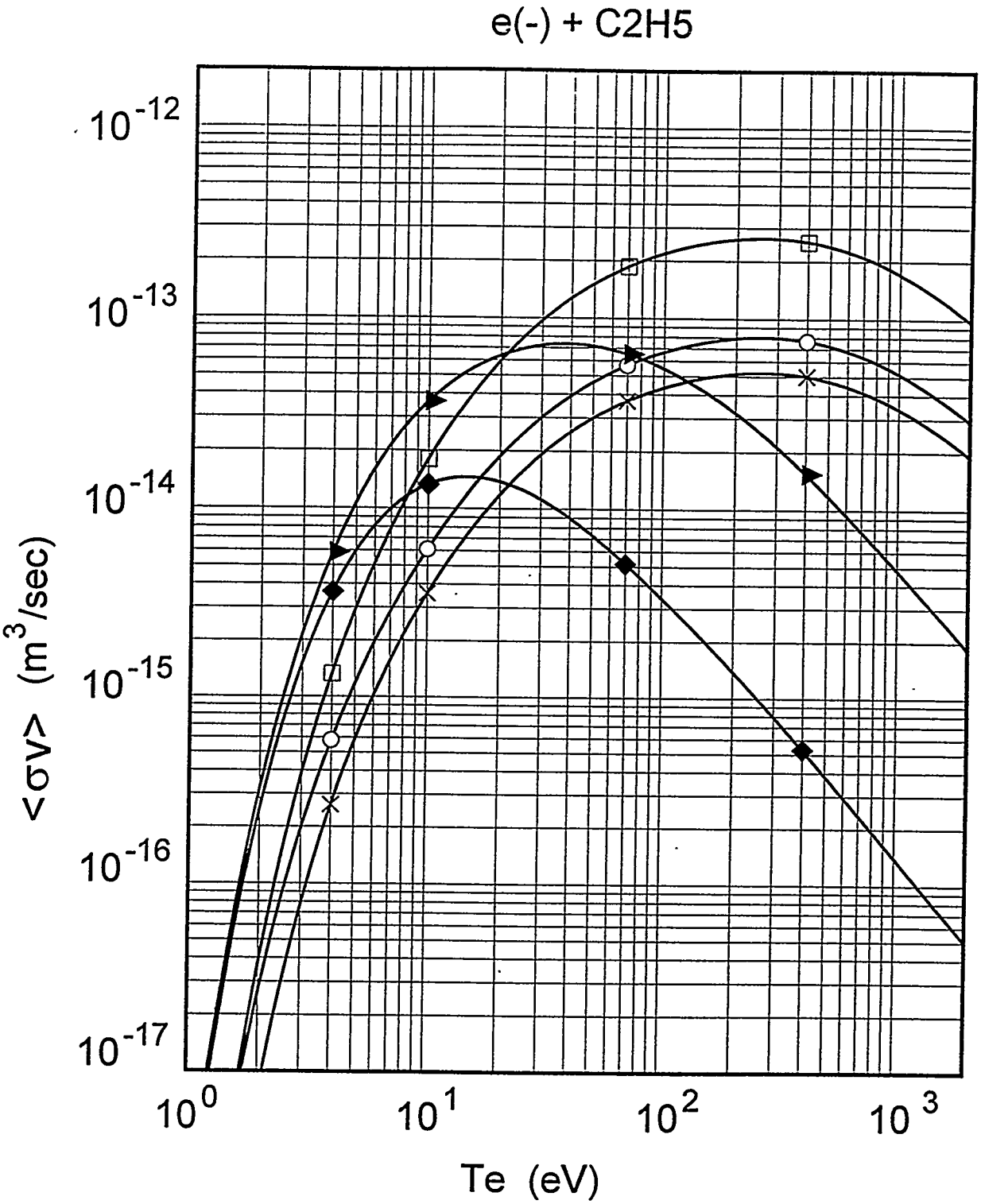

e(-) + C2H5
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
e(-) + C2H5 -> C2H5(+) + 2e(-)
e(-) + C2H5 -> C2H4(+) + H + 2e(-)
e(-) + C2H5 -> C2H3(+) + 2H + 2e(-)
e(-) + C2H5 -> C2H4 + H + e(-)
e(-) + C2H5 -> C2H3 + 2H + e(-)

Fig. 10

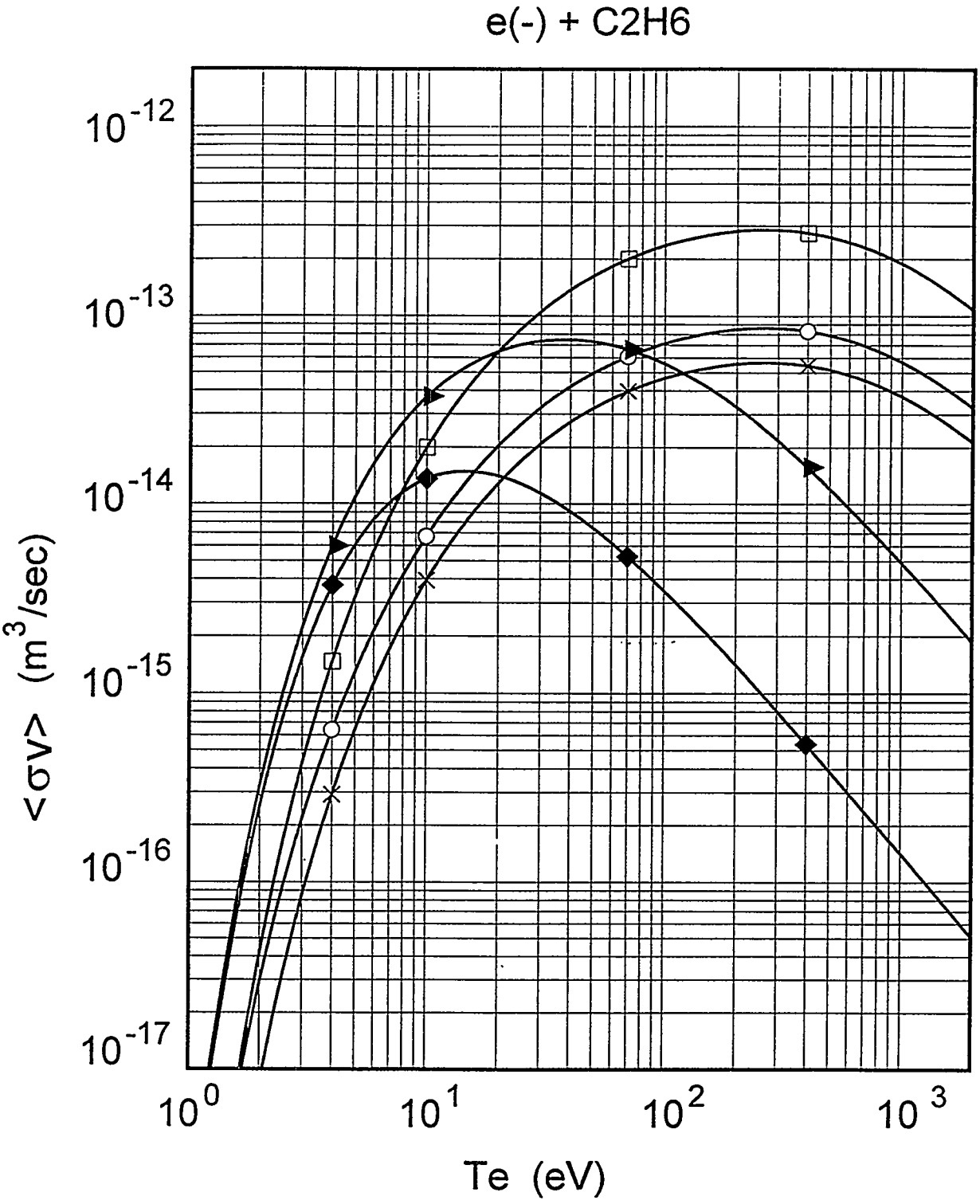

e(-) + C2H6
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
e(-) + C2H6 -> C2H6(+) + 2e(-)
e(-) + C2H6 -> C2H5(+) + H + 2e(-)
e(-) + C2H6 -> C2H4(+) + 2H + 2e(-)
e(-) + C2H6 -> C2H5 + H + e(-)
e(-) + C2H6 -> C2H4 + 2H + e(-)

Fig. 11

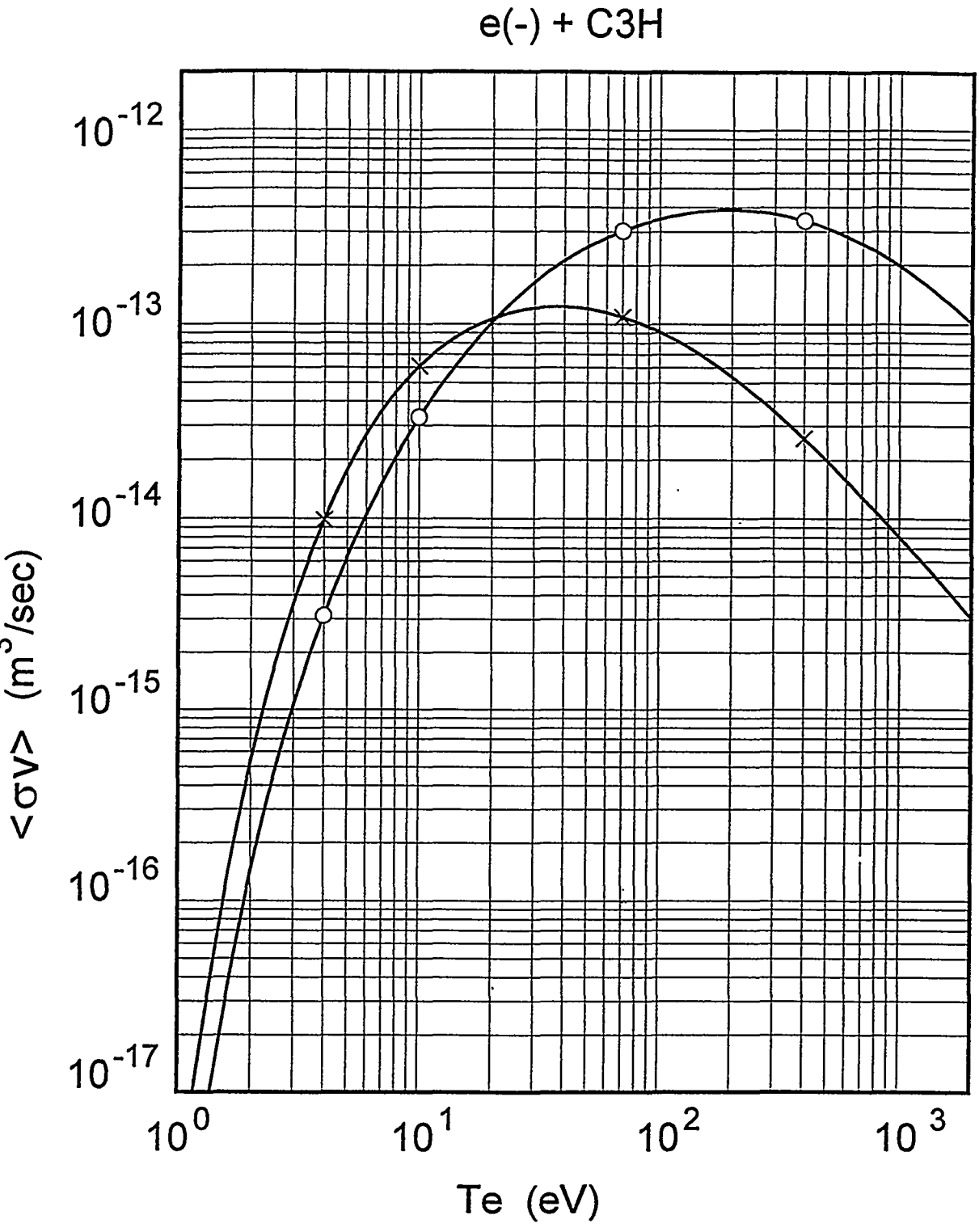

e(-) + C3H
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
o e(-) + C3H -> C3H(+) + 2e(-)
× e(-) + C3H -> 3C + H +e(-)

Fig. 12

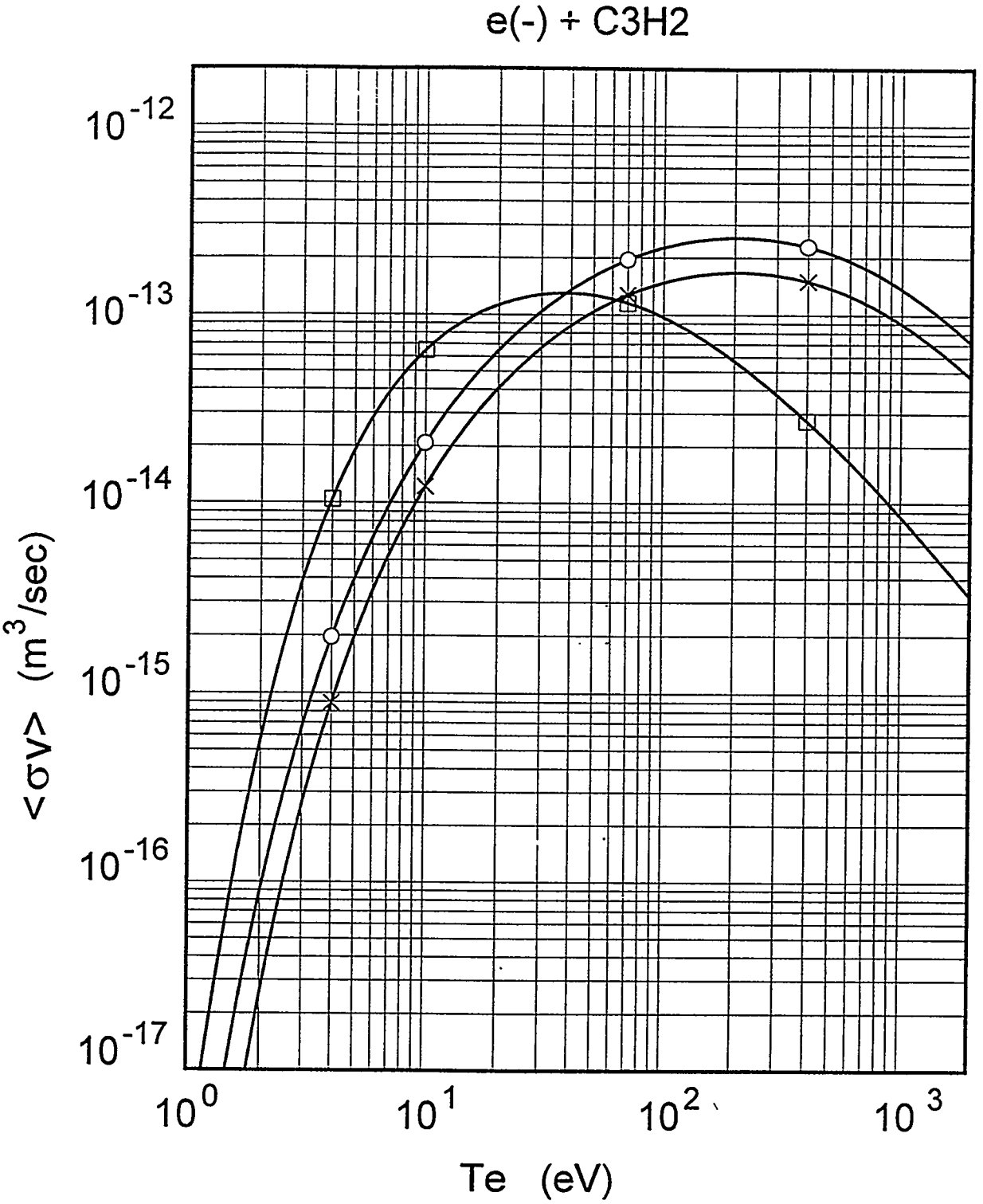

e(-) + C3H2
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m^3/sec)
10^0
10^1
10^2
10^3
Te (eV)
o e(-) + C3H2 -> C3H2(+) + 2e(-)
× e(-) + C3H2 -> C3H(+) + H + 2e(-)
□ e(-) + C3H2 -> C3H + H + e(-)

Fig. 13

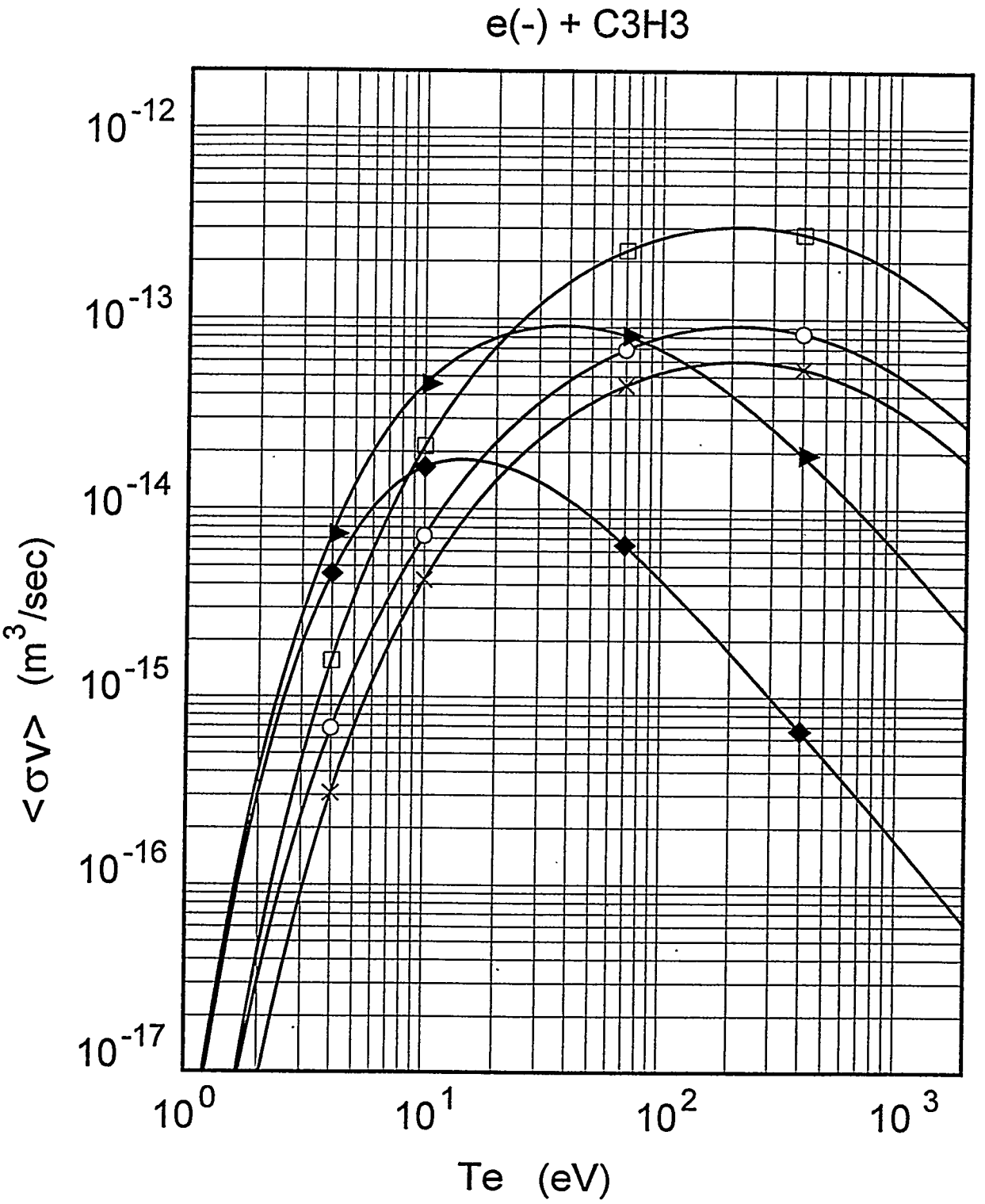

e(-) + C3H3
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m^3/sec)
10^0
10^1
10^2
10^3
Te (eV)
e(-) + C3H3 -> C3H3(+) + 2e(-)
e(-) + C3H3 -> C3H2(+) + H + 2e(-)
e(-) + C3H3 -> C3H(+) + 2H + 2e(-)
e(-) + C3H3 -> C3H2 + H + e(-)
e(-) + C3H3 -> C3H + 2H + e(-)

Fig. 14

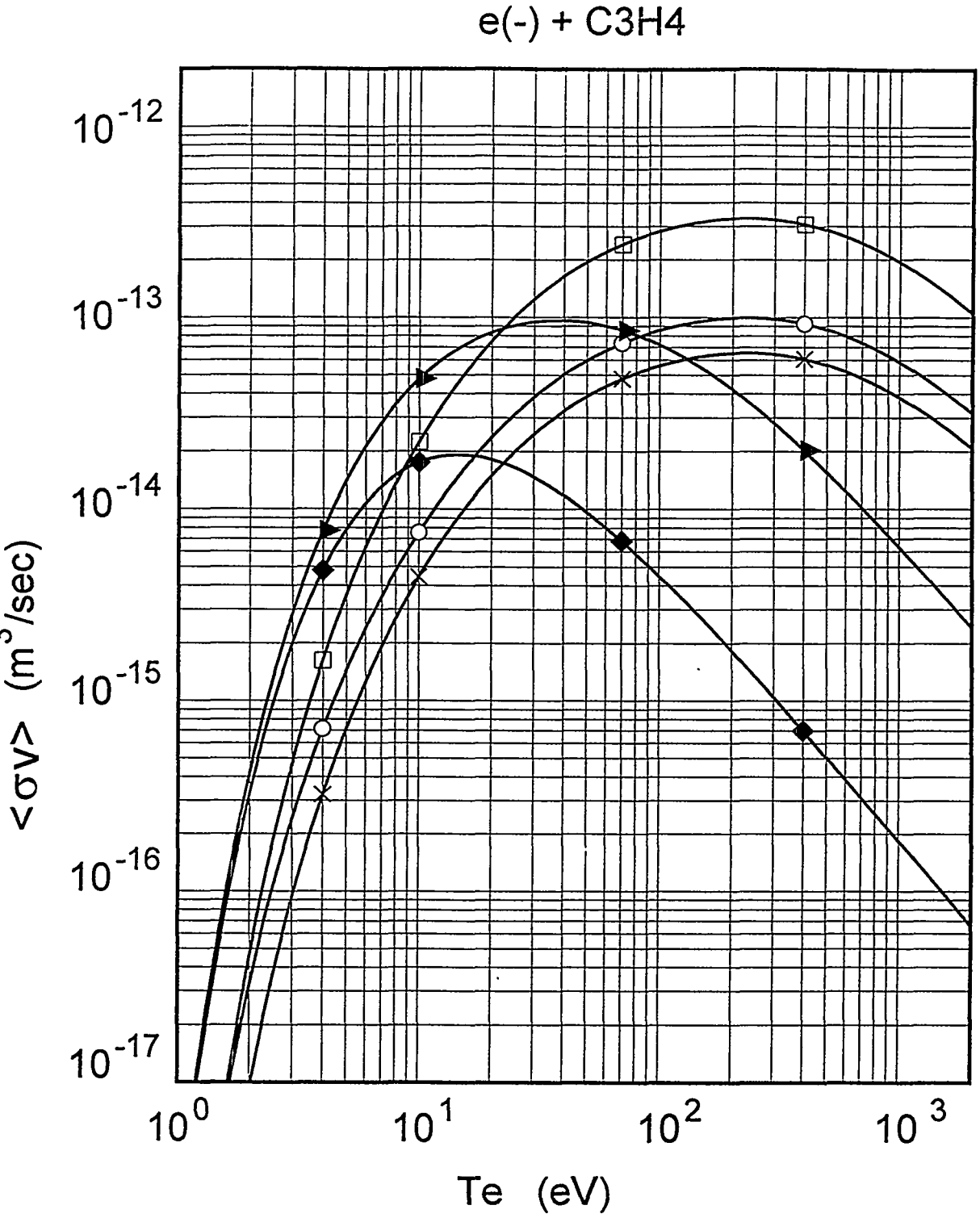

e(-) + C3H4
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
e(-) + C3H4 -> C3H4(+) + 2e(-)
e(-) + C3H4 -> C3H3(+) + H + 2e(-)
e(-) + C3H4 -> C3H2(+) + 2H + 2e(-)
e(-) + C3H4 -> C3H3 + H + e(-)
e(-) + C3H4 -> C3H2 + 2H + e(-)

Fig. 15

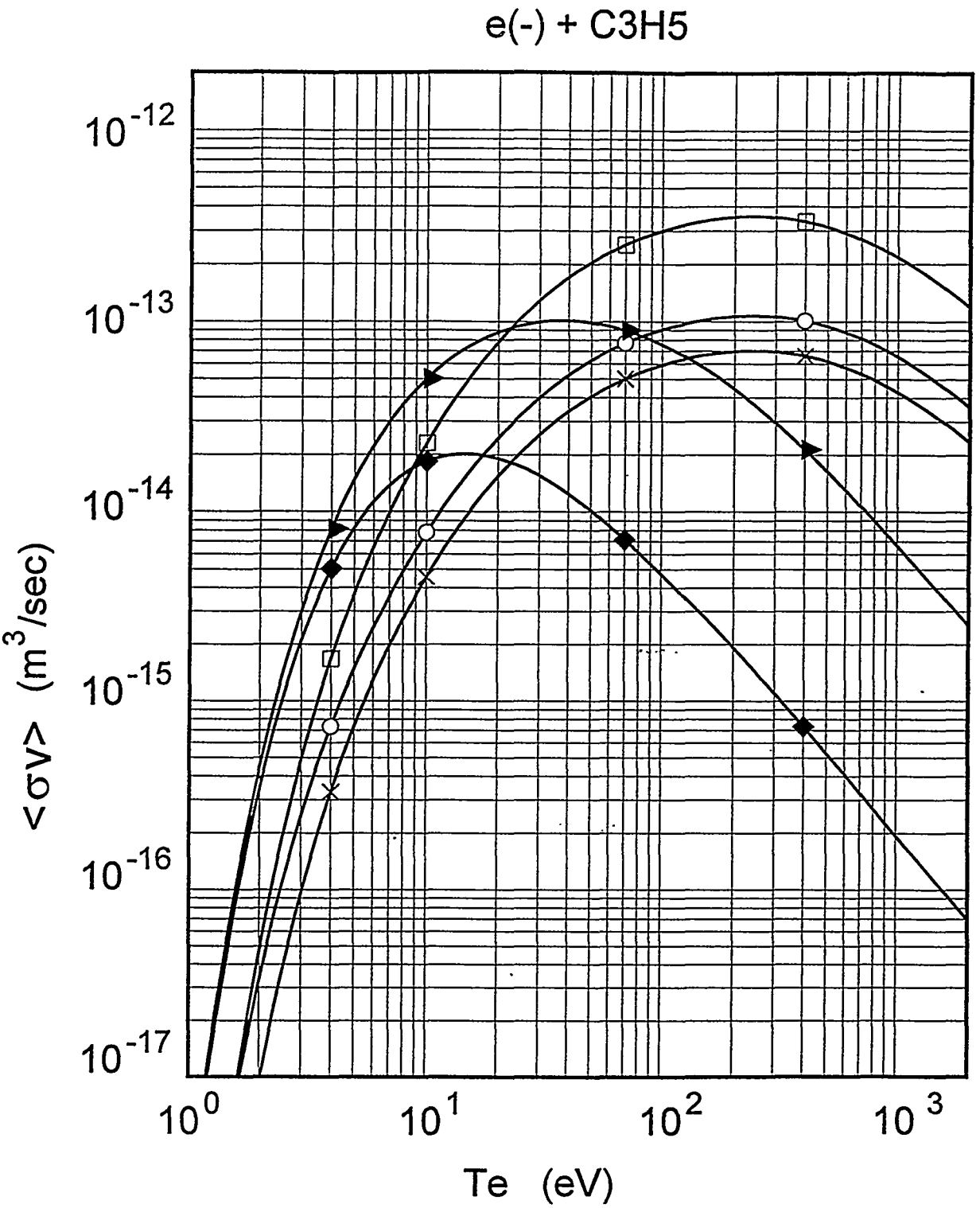
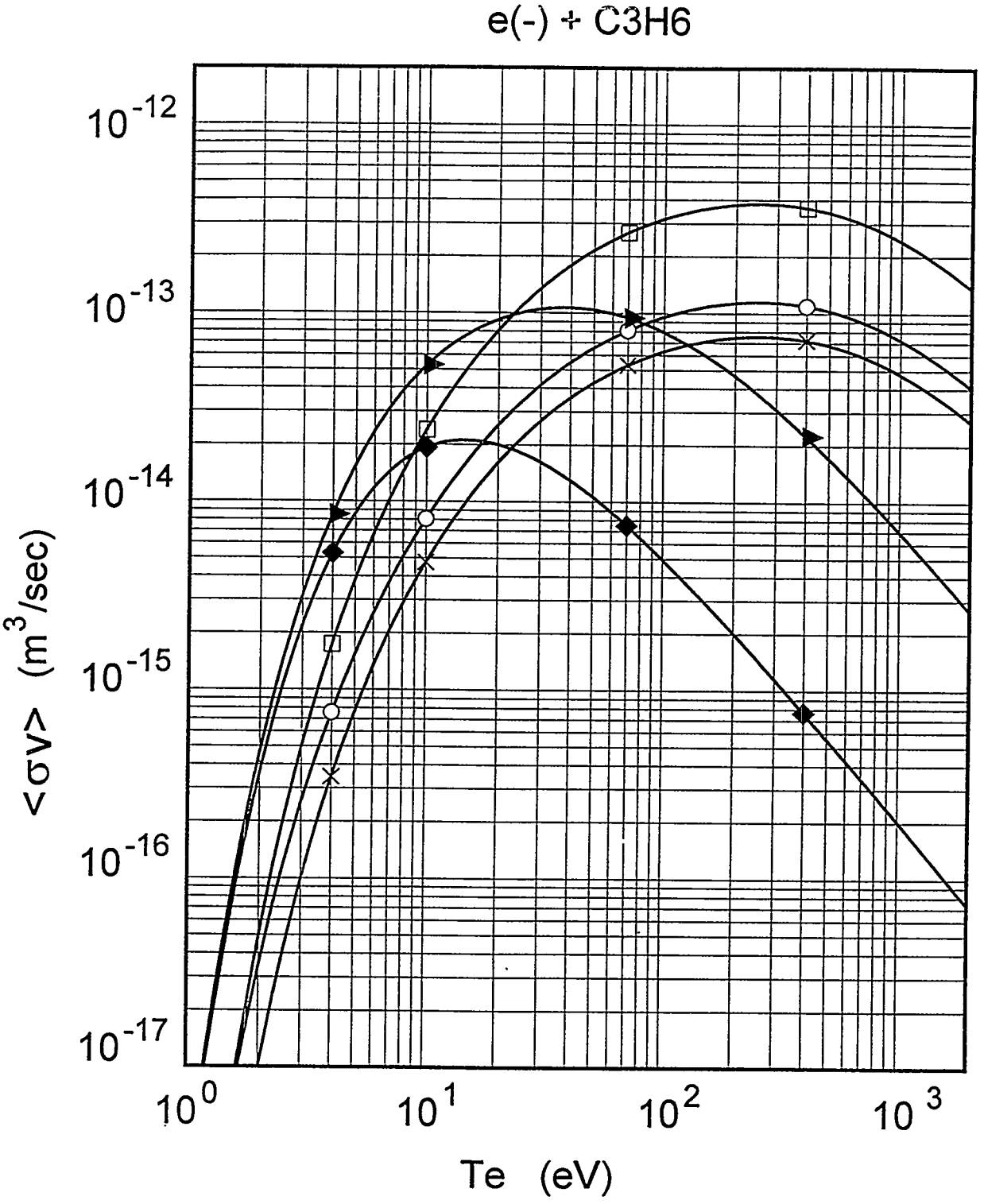

e(-) + C3H5
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
e(-) + C3H5 -> C3H5(+) + 2e(-)
e(-) + C3H5 -> C3H4(+) + H + 2e(-)
e(-) + C3H5 -> C3H3(+) + 2H + 2e(-)
e(-) + C3H5 -> C3H4 + H + e(-)
e(-) + C3H5 -> C3H3 + 2H + e(-)

Fig. 16


e(-) + C3H6
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
<σV> (m³/sec)
10^{0}
10^{1}
10^{2}
10^{3}
Te (eV)
e(-) + C3H6 -> C3H6(+) + 2e(-)
e(-) + C3H6 -> C3H5(+) + H + 2e(-)
e(-) + C3H6 -> C3H4(+) + 2H + 2e(-)
e(-) + C3H6 -> C3H5 + H + e(-)
e(-) + C3H6 -> C3H4 + 2H + e(-)

DISTRIBUTION LIST FOR ANL/FPP/TM-297

Internal

S. Bhattacharyya
J. Brooks (10)
Y. Chang
D. Ehst
Y. Gohar
D. Gruen
A. Hassanein
A. Krauss
R. Mattas
C. B. Reed
D. L. Smith
D.-K. Sze
Z. Wang (3)
FPP Files (15)
TIS File

External

ANL-E Library
ANL-W Library
DOE/OSTI, for distribution (2)
M. Akiba, Japan Atomic Energy Research Institute, Japan
D. Alman, University of Illinois, Urbana/Champaign (3)
C. Baker, University of California, San Diego
S. Berk, U.S. Department of Energy
R. Causey, Sandia National Laboratories, Livermore
R. Conn, University of California, San Diego
R. Doerner, University of California, San Diego
G. Emmert, University of Wisconsin
G. Federici, ITER-JCT, Garching, Germany
R. Goldston, Princeton Plasma Physics Laboratory
T. Haasz, University of Toronto, Canada
Y. Hirooka, NIFS, Japan
J. Hogan, Oak Ridge National Laboratory
V. Philipps, IPP, Garching, Germany
J. Roth, IPP, Garching, Germany
D. Ruzic, University of Illinois, Urbana/Champaign (3)
D. Schultz, Oak Ridge National Laboratory
M. Seki, Japan Atomic Energy Research Institute, Japan
W.M. Stacey, Georgia Institute of Technology
D. Steiner, Rensselaer Polytechnic Institute
I. Sviatoslavsky, University of Wisconsin
M. Ulrickson, Sandia National Laboratory, Albuquerque, NM
University of Illinois, Fusion Studies Lab
University of Illinois, Grainger Engineering Library Information Center
J. Van der Laan, ECN, Netherlands
J. Vetter, Forschungszentrum Karlsruhe, Germany
G. Vieider, ITER, Germany
D. Whyte, University of California, San Diego
K. Wilson, Sandia National Laboratories, Livermore
Bibliothek, Max-Planck-Institute fur Plasmaphysik, Germany
C.E.A. Library, Fontenay-aux-Roses, France
Librarian, Culham Laboratory, England
Thermonuclear Library, Japan Atomic Energy Research Institute, Japan