

Lawrence Berkeley National Laboratory

Recent Work

Title

HEATS OF CHEMISORPTION OF O₂, H₂, CO, CO₂ AND N₂ ON POLYCRYSTALLINE AND SINGLE CRYSTAL TRANSITION METAL SURFACES

Permalink

<https://escholarship.org/uc/item/6jx888h2>

Author

Toyoshima, I.

Publication Date

1978-04-01

0 0 1 0 4 8 0 0 9 2 2

UC-4
UC-90d

LBL-6664
Preprint

c.1

Submitted to Catalysis Reviews

HEATS OF CHEMISORPTION OF O₂, H₂, CO, CO₂ AND N₂ ON
POLYCRYSTALLINE AND SINGLE CRYSTAL
TRANSITION METAL SURFACES

I. Toyoshima and G. A. Somorjai

RECEIVED
LAWRENCE
BERKELEY LABORATORY

April 17, 1978

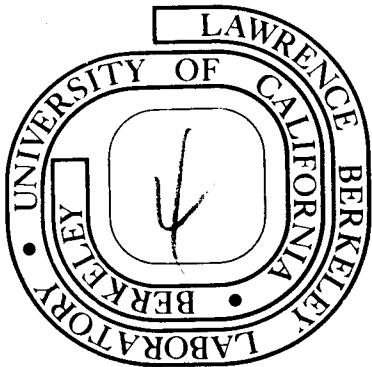
MAY 24 1978

LAWRENCE BERKELEY
LABORATORY DOCUMENTS SECTION

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

For Reference

Not to be taken from this room



LBL-6664

c.1

— LEGAL NOTICE —

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or 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.

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal 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 its 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, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

0 0 4 0 4 8 0 5 9 2 3

LBL 6664

HEATS OF CHEMISORPTION OF O₂, H₂, CO, CO₂ AND N₂ ON
POLYCRYSTALLINE AND SINGLE CRYSTAL TRANSITION METAL SURFACES

by

I. Toyoshima* and G. A. Somorjai

Materials and Molecular Research Division, Lawrence Berkeley Laboratory,
and Department of Chemistry, University of California
Berkeley, California 94720

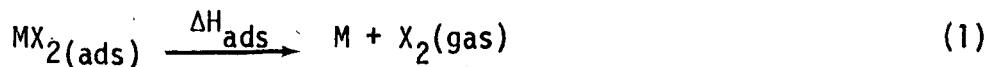
Abstract

Recent heats of chemisorption ΔH_{ads} of O₂, H₂, CO, CO₂ and N₂ obtained from polycrystalline and single crystal surfaces of transition metals have been compiled and reviewed. The single crystal surfaces exhibit many binding states with widely varying values of ΔH_{ads} . The binding energies also vary from crystal face to crystal face. The "average" heats of adsorption obtained from polycrystalline surfaces are largest for the early transition metal surfaces decreasing monotonically to reach the lowest values for Cu, Ag and Au. The heats of chemisorption have been correlated with various thermodynamic parameters that include the binding energies of bulk oxides, carbides and nitrides and gaseous carbonyls.

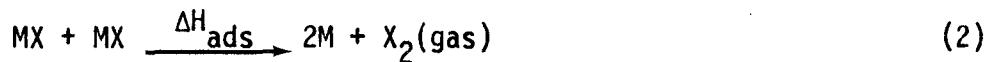
*Research Institute for Catalysis, Hokkaido University,
Sapporo, Japan.

Introduction

One of the important physical-chemical properties that characterize the interaction of solid surfaces with gases is the bond energy of the adsorbed species. The determination of the bond energy is usually performed indirectly by measuring the heat of adsorption (or heat of desorption) of the gas. In order to define the heat of adsorption, let us consider the chemisorption of a diatomic molecule, X_2 , onto a uniform solid surface, M. The molecule may adsorb without dissociation to form MX_2 . M represents the adsorption site where bonding occurs to a cluster of atoms, or to a single atom. In this circumstance, the heat of adsorption, ΔH_{ads} , is defined as the energy needed to break the MX_2 bond.



If the diatomic molecule adsorbs dissociatively, the heat of adsorption for this process is defined as



From the knowledge of ΔH_{ads} and the binding energy of the gas phase molecule, the energy of the surface chemical bond is given by

$$\Delta H_{bond} = \Delta H_{ads} \quad \text{or} \quad (3a)$$

$$\Delta H_{bond} = (\Delta H_{ads} + D_{X_2})/2 \quad (3b)$$

for the cases of molecular and atomic adsorptions, respectively, where D is the dissociation energy of the X_2 gas molecule.

There are several difficulties in determining ΔH_{ads} reliably. 1) The heat of chemisorption can markedly change with the concentration of adsorbed gas, σ . Decreasing ΔH_{ads} with increasing adsorbate concentration is commonly observed due to repulsive adsorbate-adsorbate interactions at higher coverages. Frequently the adsorbed amount is not known during a desorption experiment for example because precise measurement of the pressure is difficult. 2) The surface is heterogeneous. There are many sites where the adsorbed species have different binding energies.³ In this circumstance, the measured heat is an average of the heats of adsorption at the various binding sites. 3) The adsorbate may change bonding as a function temperature as well as adsorbate concentration.⁴ For example, oxygen may be molecularly adsorbed at low temperatures, while it dissociates to atoms at higher surface temperatures. Change of bonding with temperature as well as with coverage is frequently observed. Thus, ΔH_{ads} changes as the experimental conditions are varied. Because of these and other experimental difficulties, the heat of adsorption measurements should be repeated using different techniques of measurements to verify reproducibility. In order to understand the atomic details of the interaction of the solid surface with gases, single crystal surfaces should be used whenever possible with well defined atomic surface structure and composition.

In this paper we shall review much of the available heat of adsorption data for several small molecules, H_2 , O_2 , CO , CO_2 and N_2 , adsorbed on transition metal surfaces. Most of the data on well characterized surfaces have been reported only in recent years. We have tabulated these data and

compared them with earlier results whenever it was possible. In addition, we shall review the effect of the atomic surface structure, as revealed by studies of chemisorption on various crystal planes, on the heats of chemisorption of these gas molecules. The data reported here should be useful to predict the surface composition when two or more molecules compete for under equilibrium conditions. the same adsorption sites / The heats of chemisorption can also be used to predict when dissociation of the adsorbed molecules is likely to take place. Dissociation on the surface may be the precursor of various surface reactions.

Measurements of Heats of Adsorption on Uniform Surfaces

A) Definitions of Integral and Differential Heats of Adsorption

The total or integral heat of adsorption, ΔH_{ads} , measured for the adsorption of n molecules during the overall adsorption process is proportional to the heat of adsorption per molecule, q_{ads} ,

$$\Delta H_{ads} \approx nq_{ads} \quad (4)$$

The differential heat of adsorption, ΔH_{ads}^{diff} , is given for a one-component system by

$$\Delta H_{ads}^{diff} = \left(\frac{dH_{ads}}{dn} \right)_T = q_{ads}^o + n \left(\frac{dq_{ads}}{dn} \right)_T \quad (5)$$

where q_{ads}^o is the initial heat of adsorption, as $n \rightarrow 0$. When the differential heat of adsorption is measured under isothermal conditions, it is commonly called isothermal or isosteric heat of adsorption.*

* The relation between ΔH_{ads}^{diff} and ΔH_{ads}^{iso} is $\Delta H_{ads}^{diff} = \Delta H_{ads}^{iso} - RT$.

B) Experimental Techniques

The integral and differential heats of adsorption are usually determined by measuring the adsorption isotherms (the amount adsorbed, σ , as a function of gas pressure) for a given gas-surface system at different temperatures. From the data, the equilibrium pressure necessary to obtain the same coverage at the different temperatures are determined. From the slope of the plots of $\log p$ (at constant σ) versus $1/T$, the differential isosteric heat of adsorption, ΔH_{ads}^{diff} , can be obtained by application of the Clausius Clapeyron equation

$$[\frac{d\ln p}{d(1/T)}]\sigma = \frac{\Delta H_{ads}^{diff}}{R} \quad (6)$$

Thus the heat of adsorption for different σ can be obtained. The ΔH_{ads}^{diff} versus σ curve may be extrapolated to zero coverage to obtain q_{ads}° which is a direct measure of the interaction energy between the surface and the gas molecule.

Detailed discussions of the determination of ΔH_{ads}^{diff} from the adsorption isotherms is provided in several excellent reviews.^{5, 6}

Heats of adsorption can be determined, in addition to the use of adsorption isotherms, from calorimetry, by desorption (flash desorption or temperature programmed desorption), by field emission, ellipsometry and work function change measurements.

Calorimetry. Direct measurement of the heat of adsorption on clean, evaporated films can be made using a calorimeter which is designed to have the smallest possible heat capacity. The details of the experimental procedure and the design of the calorimeter can be found in the literature.^{1, 7, 8}

For a metal filament or ribbon, the heat of adsorption can be measured using the specimen as a resistance thermometer. Knowing the mass, the

specific heat and the temperature coefficient of resistance of the sample, the heat of adsorption can be calculated. At the beginning of the experiment the filament is cleaned by flashing to remove the absorbed species, then, it is cooled. A dose of gas is admitted to the cooled sample and is absorbed. The heat of adsorption liberated will then warm up the filament. This temperature change will cause a change in the filament resistance which can be measured accurately by a Wheatstone bridge or other suitable electronic circuit. From the change in resistance, the change in temperature can be calculated by the following correlation:

$$R_{T_2} = R_{T_1} [1 + \alpha_{T_1} (T_2 - T_1)] \quad (7)$$

where T_1 = initial temperature, K; T_2 = final temperature, °K; R_{T_1} = resistance at T_1 ; R_{T_2} = resistance at T_2 , and α_{T_1} = temperature coefficient of resistance of the sample at T_1 , $^{\circ}\text{K}^{-1}$. Then the heat of adsorption can be calculated from the change of temperature by the following equation:

$$q = \frac{ms(T_2 - T_1)}{n} \quad (8)$$

where q = heat of adsorption, cal/mole; m = mass of the filament, gram; s = specific heat of the filament, cal/gm-K and n = the absorbed amount, mole.

Thermal Desorption. Thermal desorption (flash desorption) is the most widely used technique at present for studying the kinetics of desorption rate and order of the desorption process and determining the heats of adsorption and the concentration of adsorbed molecules.^{9,10} The sample is cleaned in ultrahigh vacuum, and then a gas is allowed to adsorb on the surface at known pressures while the surface is kept at a fixed temperature. Then, the sample is heated at a controlled rate and the pressure changes during the desorption of the molecules are recorded as a function of time

and temperature. The pressure-temperature profile is usually referred to as the "desorption spectrum." The experiment is performed either in a closed system or in a flow system.

The desorption rate $F(t)$ of the species from surface of area A (cm^2) is given by

$$\frac{A}{kV} F(t) = \frac{p-p_0}{\tau_0} + \frac{dp}{dt} \quad (9)$$

where p is the pressure rise from the steady state pressure p_0 of the system prior to flashing, τ_0 is the mean residence time of gaseous species in the reaction vessel (τ_0 is defined as volume/pumping speed), V is the volume and k is a constant.

In a flow system at high pumping speeds, $\tau_0 \rightarrow 0$ and Eq. (9) is reduced to

$$\frac{A}{kV} F(t) \approx (p-p_0)/t_c = \Delta p/\tau_0 \quad (10)$$

this means that the rate is proportional to the pressure change in the system. Alternatively, for a nearly static system, at small pumping speeds, $\tau_0 \rightarrow \infty$. In this case the duration of the flashing period is short compared to τ_0 . Then the desorption rate is given by

$$F(t) = dp/dt \quad (11)$$

The desorption rate $F(t)$ is commonly expressed as

$$F(t) = - \frac{d\sigma}{dt} = v f(\theta) \exp(-E_{\text{des}}/RT) \quad (13)$$

where v is the pre-exponential factor, $f(\sigma)$ is an adsorbate concentration dependent function. The various procedures for determining these parameters are well described in the literature.

Analysis utilizing the temperature where the desorption peak is obtained is given by Redhead.¹⁰ Assuming that v and E_{des} are independent of σ and t ,

E_{des} can be obtained for zero, first and second order desorption respectively as

$$\text{zero order } E_0/R = \frac{v_0}{\sigma_0 \alpha} \exp(-E/RT_p) \quad (14)$$

$$E_1/RT_p^2 = (v_1/\alpha) \exp(-E_1/RT_p) \quad (15)$$

$$E_2/RT_p^2 = (v_2\sigma/\alpha) \exp(-E_2/RT_p) \quad (16)$$

where T_p is the temperature at which a desorption peak is at a maximum, and σ_0 is the initial adsorbate concentration. Suffix 0, 1 or 2 denotes zeroth, the first or second order desorption processes. α is a constant of proportionality for the temperature rise with time, usually $T = T_0 + \alpha t$, i.e., temperature of the sample is raised linearly with time. As seen from the equations, T_p is independent of σ_0 for the first order desorption process. Alternatively T_p is increased or is decreased with σ_0 for zeroth or second order processes, respectively. Equations 14, 15 and 16 allow one to determine the activation energy and the pre-exponential factor and also to distinguish between zeroth, first and second order desorption processes from the measurements of the dependence of the peak temperatures upon initial adsorbate concentrations and heating rate, α . Instead of a continuous temperature rise, a step-wise heating has also been used especially for studies of desorption. Advantage of this method is the more accurate evaluation of the rate constant for desorption at constant temperature and better resolution of multiple desorption peaks.

Recent determination of the heats of chemisorption on single crystal surfaces have utilized thermal desorption most frequently. The activation energy of desorption, E_{des} , for the desorption of the adsorbed species is

equal to $E_a + q_{ads}$, where E_a is the activation energy of adsorption of the same species. Therefore E_{des} cannot be equated with the heat of adsorption as long as adsorption is an activated process. However, the adsorption of several gases such as O_2 , CO , CO_2 , H_2 and N_2 on transition metal surfaces is believed not to require activation energy. In this circumstance E_{des} is a good approximation for the heat of adsorption.

Ellipsometry. Ellipsometry is a useful technique for measuring adsorption isotherms on single crystal surfaces. The amplitude and phase of the polarized light reflected from the surface change upon adsorption of a gas even at below monolayer concentrations. These changes appear to be a linear function of the "optical thickness" which is closely related to the average thickness of the adsorbed layer. By measuring the optical thickness as a function of gas pressure over a single crystal surface, the adsorption isotherm could be obtained at different temperatures. Thus the heat of adsorption could be calculated.¹² Ellipsometry can be readily combined in an up-to-date ultrahigh vacuum system, for other adsorption studies on well-defined surfaces.

Work Function Change Due to Adsorption. Adsorption is usually accompanied with a variation of the electronic work function of the metal ranging from a few tenths to more than 2 eV. Often the work function change, $\Delta\phi$, is a linear function of the adsorbate concentration and thus $\Delta\phi$ can be used to determine the adsorption isotherm.¹³ The absolute work function of the metal does not have to be known for this purpose only the work function change due to adsorption or an adsorption-related chemical change on the surface.¹⁴ The sign of the work function change shows the direction of electron transfer between the solid surface and the

adsorbate species.

The most commonly used technique of measuring the change of work function is the contact potential difference method.¹⁵ The method yields the difference in work function between two clean conductor surfaces A and B, i.e., $\phi_A - \phi_B = \Delta\phi_{AB}$, where $\Delta\phi_{AB}$ is changed upon adsorption of the gas on one of the surfaces. The other reference surface, B, is kept clean during the adsorption. Other methods for measuring work function changes such as the thermionic electron emission, photoemission, field emission, retarding potential and Kelvin methods are also being used for adsorption studies. The variation of the work function may be calibrated against the concentration of adsorbed molecules which can also be determined independently from the thermal desorption spectra. Using field emission microscopy, the heat of adsorption can also be determined from the work function change upon adsorption on the field emission tip.¹⁶ $\Delta\phi$ changes due to variation of surface concentration of the adsorbate.

Results

In Tables I-V we list the heats of chemisorption obtained for these small molecules on the different transition metal surfaces. In Tables IA, IIA, IIIA, IVA and VA, the ΔH_{ads} values that were obtained for polycrystalline surfaces are listed for O₂, H₂, CO, CO₂ and N₂, respectively. In Tables IB, IIB, IIIB and VB, the heats of chemisorption that were obtained for single crystal surfaces are given.* Variations of ΔH_{ads} for

* The methods of measurements (technique, temperature range, coverage and type of sample) also are indicated along with the references.

a given crystal face indicate the presence of multiple binding states while changes of ΔH_{ads} from crystal face to crystal face show the effects of changing atomic surface structure on the heats of chemisorption.

There have been several attempts to correlate the heats of chemisorption of small molecules on various transition metal surfaces across the periodic table. We also present the experimental data in this manner. In Figs. 1a, 2a, 3a, 4a and 5a we plot the heats of chemisorption that were obtained for polycrystalline surfaces as a function of groups of transition metals along the periodic table. Those metals having similar d-electron occupancy but belonging to the 3d, 4d and 5d rows of transition metals, respectively, are grouped together. It appears that there is a systematic decrease in the heats of chemisorption of these small molecules on transition metal surfaces from left to right across the periodic table as also indicated by previous correlations.

The data obtained for single crystal surfaces are plotted in Figs. 1b, 2b, 3b and 5b. The data is widely scattered due to the large variation of ΔH_{ads} as a result of multiple binding states for a given crystal plane and changes of ΔH_{ads} from crystal face to crystal face. However, the highest ΔH_{ads} values for each transition metal show similar correlations across the periodic table as those obtained for polycrystalline surfaces.

In order to test other correlations, we have plotted ΔH_{ads} for oxygen as a function of the heat of formation of the highest valency oxide per oxygen atom in Fig. 6. We also plot ΔH_{ads} for oxygen and hydrogen as a function of the heat of formation of the corresponding oxide or hydride per metal atom. This correlation was proposed by Tamaru,¹⁷ we have only

inserted the recent ΔH_{ads} values reported since the publication of his paper. In Fig. 8 the ΔH_{ads} for oxygen is plotted against the binding energy of the gaseous oxides.

In Fig. 9 the heats of chemisorption of CO are plotted as a function of the heat of formation of the transition metal carbide (per metal atom) while in Fig. 10 ΔH_{ads} for CO is plotted as a function of the heat of formation of the oxide (per metal atom). Both curves exhibit a break indicating the breakdown of this correlation for many transition metals. In Fig. 11 the ΔH_{ads} of CO is plotted as a function of the heat of formation of the gas phase transition metal carbonyl (per metal atom). In Fig. 12 ΔH_{ads} for CO_2 is plotted as the heat of formation of the transition metal carbide (per metal atom) and again there is a distinct break in the curve. In Fig. 13 the ΔH_{ads} of N_2 is plotted as a function of the heat of formation of the corresponding transition metal nitride per metal atom.
also

There are/interesting correlations that can be made utilizing the heats of chemisorption data obtained for H_2 and CO on different single crystal surfaces of the same transition metal. The different binding states of H_2 and CO are plotted for surfaces with 2-, 4- and 6-fold rotational symmetries for W and Ni and Pt and Pd, respectively, in Figs. 14a and 14b and 15a and 15b. It appears that the lower symmetry surfaces have more multiple binding states than surfaces with the highest, 6-fold, rotational symmetry.

In Fig. 16 we plot the ΔH_{ads} for the various binding states for H_2 on Ni, Pd and Pt single crystal surfaces. These three transition metals are in the same group in the periodic table. The variation in the ΔH_{ads} due

to the presence of multiple binding states is clearly discernable. There is no clear cut variation of the heats of chemisorption that can be identified with confidence within this group of metals from the available data.

Discussion

heats of chemisorption
The data presented in Tables I-V are clearly incomplete. There are many transition metal surfaces either in polycrystalline or in single crystal forms for which heats of chemisorption of some of the small molecules are not available. However, the recent results on polycrystalline surfaces are in agreement with earlier findings in indicating a systematic variation of ΔH_{ads} along the periodic table. The heats of chemisorption of these small molecules are the largest for the early transition metal surfaces decreasing toward the right to reach the lowest values for Cu, Ag and Au. The data obtained for the highest binding energy adsorption states on single crystal surfaces also follow this trend within the uncertainty of the experiments.

The heats of chemisorption on single crystal planes exhibit several interesting features that were not apparent up to now. There can be many binding states of an adsorbed small molecule on a given surface and their ΔH_{ads} may differ by as much as 20 kcal/mole. Thus it is not possible to identify one value for the heat of chemisorption of an adsorbate on a given transition metal unless the binding state is specified or it is certain that only one binding state exists. This observation of the existence of multiple binding states indicate that even a single crystal plane is heterogeneous when viewed by the adsorbed species. There are many binding sites of different strengths that are filled up with increasing

coverage or with changes of other experimental variables (temperature, surface structure). Inspection of Figs. 14 and 15 indicate that surfaces with two-fold rotational symmetry may have more binding states than surfaces with four-fold rotational symmetry or surfaces with the highest rotational symmetry (six-fold) crystal planes. Thus the lower rotational symmetry surfaces appear to be rougher, on the atomic scale, to the adsorbate.

It would be of value to determine trends in ΔH_{ads} for a given surface-adsorbate system in the same group in the periodic table (for example, Ni, Pd, Pt). Regrettably no such correlation is apparent for the available data (Fig. 16) within the accuracy of the experiment.

The large changes in ΔH_{ads} are particularly pronounced for the high Miller Index surfaces which have a large concentration of surface irregularities, steps and kinks. These surface irregularities are depicted in Fig. 17. These surfaces present an even more heterogeneous surface structure for the adsorbed species than crystal planes with 2-fold rotational symmetry. There are several studies that report higher binding energies for H_2 or CO, etc., at steps.¹⁸ There is evidence that CO dissociates at a kink site¹⁹ on Pt while it does not elsewhere on the surface. These sites may also be present in large enough concentrations on polycrystalline surfaces thereby contributing to the average ΔH_{ads} that is measured.

Even with the small data base that is available at present, the data may be used to predict several surface phenomena. It is possible to estimate whether dissociation of the diatomic molecules is likely to take place using the available ΔH_{ads} data and Eq. (3). It should be kept in mind that ΔH_{ads} has a large range that may indicate that dissociation

occurs at one type of site but not at another, in some cases. In case of a chemical reaction that involves two of the small molecules ($\text{CO} + \text{H}_2$, $\text{CO} + \text{O}_2$, etc.), the relative magnitudes of ΔH_{ads} for the two molecules reveal which would be present in larger concentrations on the surface. Thus the surface composition may be determined in this way.

There are several correlations suggested recently between the heats of obtained for polycrystalline surfaces chemisorption/and other system parameters that yield smooth variations along the periodic table. These parameters are inner shell atomic binding energies²⁰ or binding energies of gaseous carbonyls,²¹ etc. We have also plotted the heats of chemisorption as a function of various thermodynamic parameters of the metal-adsorbate atom (molecule) systems. With the exception of the correlation of ΔH_{ads} for O_2 with the binding energy of the highest valency oxides, the correlations are rather poor and do not seem to be very useful for predictive purposes at present.

Although thermal desorption measurements have been employed successfully to obtain heats of adsorption of many atoms and molecules on single crystal and polycrystalline surfaces, caution should be exercised in both evaluating and accepting these data. These are not thermodynamic measurements and the presence of an activation energy for desorption can modify the data. In most of these studies the order of desorption (i.e., first or second order, etc.) is assumed often using insufficient evidence along with assuming the value of the pre-exponential factor. Variation of the order of desorption and the magnitude of the pre-exponential factor markedly effect the heat of chemisorption as well.
more

It is hoped that/heats of chemisorption studies will be carried out in the near future to broaden the data base that is presented in this paper.

0 0 0 0 4 8 0 5 9 3 |

-15-

Adsorption studies on single crystal surfaces would be particularly useful as they reveal the complex effects of the atomic surface structure that appear to greatly influence the nature of chemisorption on transition metal surfaces.

Acknowledgment

This work was supported by the Division of Basic Energy Sciences, U. S. Department of Energy.

Figure Captions

- Fig. 1a Heats of adsorption of oxygen on polycrystalline transition metal surfaces.
- Fig. 1b Heats of adsorption of oxygen on single crystal surfaces of transition metals.
- Fig. 2a Heats of adsorption of hydrogen on polycrystalline transition metal surfaces.
- Fig. 2b Heats of adsorption of hydrogen on single crystal surfaces of transition metals.
- Fig. 3a Heats of adsorption of CO on polycrystalline transition metal surfaces.
- Fig. 3b Heats of adsorption of CO on single crystal surfaces of transition metals.
- Fig. 4 Heats of adsorption of CO_2 on polycrystalline transition metal surfaces. Filled symbols indicate differential heats of adsorption.
- Fig. 5a Heats of adsorption of N_2 on polycrystalline transition metal surfaces.
- Fig. 5b Heats of adsorption of N_2 on single crystal surfaces of transition metals.
- Fig. 6 Heats of adsorption of O_2 for transition metals as a function of the heats of formation of the highest valence oxides (per oxygen atom).
- Fig. 7 Heats of adsorption of O_2 and H_2 for transition metals as a function of the heats of formation of the corresponding oxides and hydrides (per metal atom).

- Fig. 8 Heats of adsorption of O_2 on transition metal surfaces as a function of the bond energies of the gaseous monoxides and dioxide.
- Fig. 9 Heats of adsorption of CO on transition metal surfaces as a function of the heats of formation of the carbides (per metal atom).
- Fig. 10 Heats of adsorption of CO on transition metal surfaces as a function of the heats of formation of the oxides (per metal atom).
- Fig. 11 Heats of adsorption of CO on transition metal surfaces as a function of the heats of formation of gaseous carbonyls. • = caloimetric studies, o = thermal desorption, □ = thermal desorption, lowest energy binding states.
- Fig. 12 Heats of adsorption of CO_2 on transition metal surfaces as a function of heats of formation of carbides (per metal atom).
- Fig. 13 Heats of adsorption of N_2 on transition metal surfaces as a function of heats of formation of nitrides (per metal atom).
- Fig. 14a,b Heats of adsorption of H_2 on tungsten and nickel crystal surfaces, respectively, that have 2-, 4- and 6-fold rotational symmetries.
- Fig. 15a,b Heats of adsorption of CO on platinum and palladium crystal surfaces, respectively, that have 2-, 4- and 6-fold rotational symmetries.
- Fig. 16 Heats of adsorption of H_2 on single crystal planes of Ni, Pd and Pt, metals in the same group in the periodic table.

Fig. 17 Schematic representation of the heterogeneous surface on the atomic scale. The different surface sites are distinguishable by their number of nearest neighbors and atomic structure.

0 0 0 0 4 8 0 5 9 3 3

-18-

References

1. D. O. Hayward and B. M. W. Trapnell, Chemisorption, (Butterworth London, 1964).
2. Chemisorption and Reactions on Metallic Films, ed. J. K. Anderson (Academic Press: N.Y. 1971).
3. G. A. Somorjai and J. C. Buckholz, Accts. Chem. Res. 9, 331 (1976).
4. G. A. Somorjai, Angew. Chemie 16, 92 (1977).
5. J. G. Dash, Films on Solid Surfaces (Academic Press: N.Y. 1975).
6. A. Clark, The Theory of Adsorption and Catalysis (Academic Press: N.Y. 1970).
7. O. Beeck, W. Cole and A. Wheeler, Disc. Faraday Soc. 8, 314 (1950).
8. S. Cerny and V. Ponec, Cat. Rev. 2, 249 (1968).
9. D. Menzel, Interactions on Metal Surfaces (Springer-Verlag: Berlin 1975).
10. P. A. Redhead, Vacuum 12, 203 (1962).
11. K. F. Steiger, J. M. Morobito, Jr., G. A. Somorjai and R. M. Muller, Surf. Sci. 14, 273 (1969).
12. F. Meyer, Surf. Sci. 56, 37 (1976).
13. J. C. Riviere, Solid State Surf. Sci. 1, 1 (Dekker, N.Y., 1969).
14. J. L. Gland and G. A. Somorjai, Surf. Sci. 41, 387 (1974).
15. P. P. Craig, V. Radeka, Rev. Sci. Instr. 41, 258 (1970).
16. B. E. Nieuwenhuys and W. M. H. Sachtler, Colloid and Interface Science 1, 69 (1976).

0 0 4 0 4 8 0 5 9 3 4

-19-

17. T. Kandow and K. Tamari, Kagaku Kyoiku 24, 40 (1976).
18. K. Christmann, G. Ertl and T. Pignet, Surf. Sci. 54, 365 (1976).
19. R. Mason and G. A. Somorjai, Chem. Phys. Letters 44, 468 (1976).

TABLE IA

Heat of Adsorption of O₂ on Polycrystalline Surfaces

Metal	Form	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Ag	plate	216~226 K	8.3	calorimetry cal. isotherm	1
	porous	383 K	130→10 (θ0→1)		2
	powder	773 K	41.8±3.5		3
Al	film	RT	211-159	cal.	4
Au	porous	140 K	103 →	cal. (wide range θ)	5
Co	film	RT	100 →	cal.	4
	film	RT	98 →	cal.	6
	film	77 K	84 →	cal.	6
Cr	film	RT	174 ↓	cal.	4
Cu	plate	207~223	5.2	cal.	1
	film	273 K	109.8-20		7
Fe	film	RT	136 →	cal.	4
	film	RT	71 →	cal.	8
	film	273 K	99-120 →	cal.	9
Ge	film	RT	131 ↓	cal.	10
Ir	ribbon	RT	38.1±3 71.5±2	thermal desorption (second order)	11
Mn	film	RT	152 →	cal.	4
Mo	film	RT	172 →	cal.	4
	film	RT	192 →	cal.	6
	film	77 K	170 →	cal.	6
	filament	1800-2200 K	132	TD TD (2 states)	12
	ribbon	RT	60 110		13
Ni	film	RT	120~130	cal.	14
	film	RT	115 →	cal.	4
	film	RT	107 →	cal.	6
	film	RT	140~150 +	cal.	15
	film	273 K	76~89 →	cal.	16
	film	90 K	71 →	cal.	6
	film	77 K	70 →	cal.	6
Pd	film	RT	67	cal. mean value	4

Metal	Form	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Pt	film	RT	69~72 +	cal.	4
	filament	298 K	58 +	TD atomization	17
	filament	RT	54(β_4) 39(β_2)	TD (first order) TD (first order)	18 18
Re	film	RT	175	cal.	10
	filament	RT	≤ 92	TD	19
	filament	1600-2200 K	127	TD	12
	filament	RT	127	TD	20
Rh	film	RT	120+	cal.	4
Si	film	RT	218+	cal.	10
Ta	film	RT	212 +	cal.	4
Ti	film	RT	236 +	cal.	4
W	film	RT	183	cal.	6
	film	RT	194	cal.	4
	filament	303 K	139	cal.	21
	film	77 K	184	cal.	6
	film	90 K	184	cal.	6
	ribbon	RT	53} 106	TD TD	22
	tip	RT	92~115	field emission microscopy	23
	ribbon	RT	139 97 }	TD (atomic desorp.) oxide evap.	24
	filament	RT	76.1 110.7}	2 states	19
	filament	2000-2150 K	135	TD, FEM	25
	filament	RT	161	TD	12
ribbon	2000-2700 K		145}	$\theta=0$ TD	26
			83	$\theta=1$ TD	

TABLE IB
Heat of Adsorption of O₂ on Single Crystal Surfaces

Metal	ΔH_{ads} (kcal/mole)	Technique	Ref.
Ag(110)	~40	TD isothermal	27
Ag(111)	35-45	TD	28-30
Cu(110)	50	TD	31
Ge(111)	64.6±11.5	mass desorbed GeO	32
Ir(111)	65	TD	33
Mo(100)	118	TD	34
Pd(110)	80~48	isotherm	35
Pd(100) (110) (111)	55	isotherm	36
Pt(100)	44.7(β_1) 62.1(β_2) 69.3(β_3)	TD	37a
W(100)	120-173	isosteric TD	38
(100)	136	TD	34
(100)	93.2	TD atom	39
W(110)	139		34
(110)	92.0	FEM, TD	40
W(111)	23.1	TD	41

TABLE IIA

Heat of Adsorption of H₂ on Polycrystalline Surfaces

Metal	Form	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Co		RT	24.1 ($\theta \rightarrow 0$)	cal.	42
Cr	film	RT	45.0	cal.	43
Cu	filament	250-400 K	43.5(calculated)	TD	44
	film	242-337 K	9.6-11.9	work function	45
	film		8~12	work function	46
Fe	film	RT	32 +	cal.	43
	film	90 K	32 -	cal.	113
	film	77 or 90	27.5 +	cal.	48, 14
	film	306-583 K	~16(9.3-21.7)	isosteric $\theta=0.8$	49
	filament	RT	20 +	TD	50
Ir	filament	100 K, 300 K	24	TD	51
	filament	RT	26.1($\theta \rightarrow 0$)		42
Mn	film	78, 193, 295 K	12.0	TD	52
	film	298 K	17.1	isotherm	53
Mo	film	293 K	40	cal. ($\theta=0$)	54
	film	77-373	34	isosteric $\theta=0.45$	55
	filament	300-1000 K	~7(estd., $\theta=0.6$)	TD	81
Ni	film	RT	25.5 +	cal.	56
	film	294 K	28 +	cal.	54, 57
	film	RT	11-38.4	cal.	15
	film	RT	30.0	cal.	14
	film	RT	31.0	cal.	43
	disk	~273 K	30 +	cal., isosteric	134
	film	77, 273	18.0 +	cal. ($\theta=0 \sim 0.8$)	58, 59
		77	18 +		
		273 K	18 +		
	tip	4, 2 K	68-72	FEM	60
	tip	345-357 K	46 ± 4	FEM (low θ)	61
	film	RT	31.5 (extrapolated)	isosteric ($\theta=0$)	62
	film	273 K	20 +	isosteric $\theta=0.91$ +	63
	film	RT	25-10	isosteric $\theta=0.8$	64
	film	RT	16.0 $\theta=0.1, 0.75$	2 states	65
			15.0 $\theta=0.5$		
	filament	86	38.2 }	cal.	66
		279	52.6		
	film	90 K	30 +	cal.	113
		296 K	31 +		

Metal	Form	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Pd	filament	200	22(β_1) 25(β_2) 35(β_3) } 28	TD	67
	film	RT	13~14(α) }	cal.	43
Pt	film	278~295 K	8(γ) 12(β_1) 21(β_2)	TD	68
	tip	4.2~320	16	FEM	69
	foil	140~600 K	16~5	TD (isosteric)	70
	filament	300	26.0(β)	TD	71
	tip	83~293 K	15	work function	194
Re	ribbon	RT	27.5(first order) 67 (second order)	TD	73
Rh	film	RT	28 +	cal.	43
	filament	100, 300 K	18	TD	51
Ta	film	300 K	30 +	cal.	113
	film	RT	45 +	cal.	43
	filament	RT	82	TD	74
Ti	film	273 K	39 + (39~22)	cal.	75
	film	77 K	27.5 + (27.5~10)	cal.	76
W	film	RT	45 +	cal.	43,14
	film	RT	46.5 +	cal.	56
	film	294 K	52 +	cal.	57
	filament	79 K	45 +	cal.	77
	filament	RT	28	cal.	78
	film	90 K	35 +	cal.	56
	film	195	42 +	cal.	56
	filament	77 K	31 +	TD isothermal	79
	filament		36 +	TD	80
	filament	300~1000 K	~7(esdt., $\theta=0.6$)	TD	81
	filament		35	TD	82
	filament	RT	25.5, 29.0	TD	83
	tip	78 K, 300 K	20~46 15~20 8~14 6~10 } FEM (4 states)	FEM (4 states)	72
	filament	100 K, 300 K	35	TD	51
	tip	4.2 K	64 +	FEM (low θ)	60,84
	tip	4.2 K	6	TD (110 boundary)	84
--	film	90~273	42 +	isosteric	85
	filament	300 K	15	TD isosteric $\theta=0.7$	79
	filament	77	31 +	isosteric($\theta=0.1$)	79
	--	RT	45.9(calculated) 44.0(observed) } $\theta\rightarrow 0$	--	42

TABLE IIB

Heat of Adsorption of H₂ on Single Crystal Surfaces

Material	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Cu(311)	251-297	9.3→9.2→9.9	IR isosteric	86
Ge(111)	?	18.5±2.3	TD	32
Mo(100)	78	16(β_1) 20(β_2) 27(β_3)	TD	87
Mo(110)	78	28±1(β_1) 34±1(β_2)	TD	88
Ni(100)	RT	23.1	TD	89
Ni(110)	298-315 K 299-345 K	19.5(α) 29.5(β)	isosteric TD isotherm TD	90
Ni(110)	282 K	20.3 (low θ)	isotherm TD	91
Ni(110)	333-400 K	27.7	isosteric TD	92
Ni(111)	RT	21.4±1} calc. 22.7±1} exp.	isotherm TD	93,47
Ni(100) (110) (111)	RT	23.0(β_1, β_2) 21.5(β_1, β_2) 23.0(β_1, β_2)	isosteric	94
Ni(110)	RT	23.5	TD (2 states)	95
Pd(110) (110) (111) (111) [Pd(S)9(111)x(111)]	RT	24.4} D ₂ 22.8 20.8} H ₂ 23.8	isosteric ($\theta=0$)	96
Pt(100) (111)	RT	15~16	TD	97
	RT	18	molecular	98
		31	dissociative	
(111)	150	9.5(β_2)	TD	99
(111)	RT	15~20	isotherm	
		30~32		
Ta(110)	RT	10	estm.	101
W(100)	78	26.3(β_1) 26.6(β_1) 32.3(β_2) 32.6(β_2)	H ₂ , TD D ₂ , TD H ₂ , TD D ₂ , TD	102

Material	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
W(110)	78	27.0±1(β_1) 32.7(β_2) 14.1 (β_1) 21.7 (β_2) 30.4 (β_3) 36.6 (β_4) 6~11 (γ)	TD	103
(211)	110	16 (β_1) 35 (β_2)	TD	104
(211)	78 K, 300 K	46	FEM	72
(100)	78 K	26 (β_1) 32 (β_2)	TD	87
(110)	180-220 K	65-82(boundary free) 60(boundary)	FEM	60

TABLE IIIA

Heat of Adsorption of CO on Polycrystalline Surfaces

Metal	Form	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Ag	supported on Al_2O_3	303 K	18~20	IR	105
	film	194.5, 209.5 K	8.7	isothermal	106
	supported on Al_2O_3	303 K	18-20	IR	105
Co	film	273 K	47 →	cal.	107
		303 K	18-20	IR	105
Cu	film	194.5, 209.5 K	9.3	isothermal	106
	supported on Al_2O_3	303 K	18-20	IR	105
Fe	film	273 K	46 ↓	cal.	107
	film	RT	32 ↓	cal. iso.	108
	film	77 K	10 ↓	cal. iso.	14
	film	90-306 K	4-20	$\theta=0.8$	49
Ge		RT	>26	TD	109
Ir	supported on Al_2O_3	303 K	>50	IR	105
Mn	film	273 K	78 ↓	cal.	107
Mo	film	273 K	74 ↓	cal.	107
	filament	RT	4.6	TD	110
			20.3	physical	
			65.7		
			30.4		
		1073 K	74.7	tracer	112
		1123 K	78.6	TD	
		1073,1123 K	83.2		
		1073,1123,1173 K	86.9		
		1123,1173 K	91.1		
	ribbon	RT	35(α)	TD, ESD	111
	filament	300 K	20.3,30.4,65.7	TD	133
Nb	film	273 K	125 ↓	cal.	107
Ni	film	273 K	42 ↓	cal.	107
	film	RT	35 ↓	cal.	14
	film	RT	33	cal.	15
	film	273 K	25.0-30.1 8.4-25	cal. (diff.) 2 states	114

Metal	Form	Temperature	H_{ads} (kcal/mole)	Technique	Ref.	
Ni	film	90 K	$35(\theta=0.74) \rightarrow 4.5(\theta=1)$		115	
	film	RT	$4.4(\alpha)$ $32(\beta)$	TD	116	
	plate	RT	25	TD tracer	117	
	filament	300 K	6.5, 52.6	TD	133	
	film	RT	24-17	isosteric	118	
Pd	film supported on Al_2O_3	273 K 303 K	$43 \rightarrow$ ≥ 38	cal. IR	107 105	
Pt	supported on Al_2O_3	303 K	≥ 44	IR	105	
	tip	RT	32 (low θ)	FEM	72	
	film	273 K	$48 \rightarrow$	cal.	107	
	foil	RT	$\theta=0-0.8$ $\theta=0.8-6$ $\theta=6-9$	34 ± 2 (28 ± 3) 28 ± 2 (19 ± 3) 22 ± 2 (9 ± 4)	TD 1st order	119
	ribbon	300 K	32.27	TD	159	
Re	filament	RT	36(α) 54(β)	TD	120	
	filament	RT	50(α) 69.6(β)	TD	121	
	filament	RT	23.1 (α_1) 27.7 (α_2) 46.2 (β_1) 55.3 (β_2) 62.3 (β_3)	4 states		
				TD exchange	122	
Rh	film supported on Al_2O_3	273 K 303 K	$46 \rightarrow$ ≥ 44	cal. IR	107 105	
Ta	film	273 K	134 \rightarrow	cal.	107	
Ti	film	273 K	153 \rightarrow	cal.	107	
W	filament	RT	53 75 100	TD	123	
	filament	RT	20 75 100	TD	124	
	filament	RT	18.7 51.7 67.6 77.5	TD	125	

Metal	Form	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
W	filament	RT	29 59 69.5 75.5	TD	126
			23 63 77 90	TD	127
	filament	RT			
		300 K	18.7, 51.7 67.6, 77.5	TD	133
	tip	20 K	16 44 76	FEM heat of ads.	128
	tip	78 K	20 52 70 100	FEM	72
	tip	4.2 K	36 52	FEM	129
	film	RT	14.8	cal. $\theta=0.72$ isotherm.	130
	film	RT	8.0($\theta=0.84$), 3.6($\theta=1.02$)	cal. isothermal	130
	filament	RT	13 30 89	TD	131
Zr	film	273 K	150 +	cal.	107

TABLE IIIB
Heat of Adsorption of CO on Single Crystal Surfaces

Metal	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Ag(111)	66-123 K	6.5, 4.3	isotherm., isosteric	132
Co(0001)	300 K	4.2 16.8 47.0	TD	133
Cu(100)	77 K	14.5	isosteric	135
Cu(100)	77-300 K	16.6, $\theta=0$ 11.5, $\theta=0.5$	isosteric isosteric	136 136
Cu(311)	77-300 K	14.6-10.8	isobar	137
Ir(110)	RT	37 (mean)	TD	138
Ir(111)	RT and below	35±1	iso. $\theta=0.33$	139
Ir(111)	RT	45	$\theta<0.33$	140
Ir(111)	RT	39±3	$\theta=0.33$ TD	140
Ir(111)	RT	43.9	$\theta<0.3$ TD	141
Ni(100)	350 K	30.0	iso.	136
Ni(110)	300 K	3.9, 13.8, 45.7	TD	133
Ni(100)	200, 298 K	26.1	tracer isotherm	142
Ni(110)	RT	3.9, $E_3(\alpha)$, 45.7, $E_1(\beta)$ 13.8, E_2 (intermediate)	TD	125
Ni(110)	182, 298, 287 K	25.3	tracer isotherm	142
Ni(110)	RT	25 ~30	$\theta>0.7$ isotherm $\theta<0.7$ isotherm	143
Ni(110)	128-300 K	25.4 30.0	TD isosteric	144

0 0 0 0 4 8 0 3 3 -31- 4 0

Metal	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Ni(110)	RT	22.5	TD relaxation TD	145
		26.4		146
		33±1		147
		32.7		
Ni(111)	RT	23.5	$\theta=0.33$ isotherm $\theta=0$	148
		26.5		
Mo(100)	RT	62±4	TD	149
		79±4		
		86±5		
Mo(100)	RT	65.7	TD	150
		70.3		
		74.7		
		77.3		
		81.6		
Nb(110)	300 K	69	TD	133
		15		
		33.7		
		39.9		
		57.0		
		6.9		
Pd(100)	77 K	35.7 ($\theta=0$), 27.7 ($\theta=0.5$)	isotherm iso.	151
Pd(100)	RT	36+	LEED	152, 154
Pd(110)	300 K	4.8	TD	133
		9.0		
		45.2		
		55.3		
Pd(100)		30	isothermal	36
Pd(111)	RT	34→32+	isotherm	153
Pd(110)		30	isothermal	36
Pd(110)	RT	41(5x2), 27(2x1)	isotherm	155
Pd(111)		30	isotherm	36
Pt(100)	RT	32		156
(110)	RT	25.1 (α)(sat'd) 30.8 (β)(sat'd)	TD TD	157
(110)	333 K	31.8 ± 0.9 (\rightarrow sat'd) isosteric 25.1 28.7 31.4	TD	158

Metal	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Ru(100)	RT	29.6 22.2 23.5 } 28.	$\theta < 0.6$ $\theta > 0.6$ TD	160
Ru(101)	300 K	25.1, 28.2	TD	161
W(100)	300 K	93±5 (β_3) 74±4 (β_3) 62±4 (β_3) 57±4 (β_1^2); 21±2 (α)	TD	162
W(100)	RT	27±4 } 57±4 } 64±4 } 82±5 }	TD	149
W(110)	320 K 1000-1100 K -- 320 K > 1000 K 20-400 K	6.8, 10, 10-25 55(β_1) Arrhenius 69.5±3 (β_1) 9.5 } 40 } (β_1) 66.0 } (β_2)	isothermal D stepwise D	163 163
W(110)	300-1100 K	80.7-23.1	TD($\theta \uparrow$)	164
W(113)	300-1100 K	87.6 -27.7	TD($\theta \uparrow$)	164
W(110)	4.2 K	52 (boundary) 90 (boundary-free)	FEM	60

TABLE IVA

Heat of Adsorption of CO₂ on Polycrystalline Surfaces

Metal	Form	Temperature	ΔH_{ads} (kcal/mole)	Integral	Calc.	Ref.
Co	film	RT	37 +	35	29	165
Cr	film	RT	115 +	81	-	165
Fe	film	RT	67 +	61.5	46.5	165
Mn	film	RT	63 +	53	85	165
Mo	film	RT	107 +	89	92	165
Nb	film	RT	162 +	132	168	165
Ni	film	RT	54 +	44	28	165
Ta	film	RT	182 +	168	172	165
Ti	film	RT	187 +	163	203	165
W	film	RT	120 +	109	155	165

TABLE VA

Heat of Adsorption of N₂ on Polycrystalline Surfaces

Metal	Form	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Fe	film	77 K	10 +	cal. cal.	113
	film	RT	70 +		108
	film	90 K	5 +	cal.	166
Ni	film	78 K	<7 6~10 9-14	TD	167
	film	77 K	10 +		113
Nb	filament	RT	>120	TD	168
Ir	filament	RT	58	TD	169
Mo	filament	RT	62.3(ζ), 71.5(ϵ)	TD	170
	filament	RT	69.2(ζ), 83.0(ϵ)	TD	195
	filament	RT	60.5 \pm 2	TD	171
	filament	RT	\sim 80	TD	168
	film	78-300 K	6-20	TD	172
Pd	film	78 K	<7 6~10 (2 states)	TD	167
Re	filament	RT	67.9-74.9(β)	TD TD exchange	122
	film	RT	66.9-73.8 (β)		122
Ta	film	300 K	140 \rightarrow	cal. TD	113
	filament	RT	>120		168
W	filament	RT	92.2 \rightarrow 80.7 \rightarrow 115	cal. cal.	173
	film	RT	95 +		14
	ribbon	196, 300, 473 K	116	($\theta \rightarrow 0$) isosteric	174
	film	195, 290 K	14-24	(molecular) TD FEM	176
	filament tip	RT 20, 77, 290 K	\sim 80 153 (E_{des})		168 177
		243 K	81	TD	180
		77, 300 K	154.5	FEM	178

Metal	Form	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
W	filament	~115 K ≤400 K ~100 K	~ 9 } (γ) ~ 20 } (α) 58-81	TD	175
	ribbon/filament	RT	110/75	TD	181
	filament	<373 K	diff 95, 150	TD	182
	ribbon		92 (des.)	TD	183
	ribbon	> RT	0.1($\theta=0\text{--}1.0$), 5.0($\theta=2.0$)	TD	23
	filament	RT	1.84(ϵ), 1.61(ζ), 18(α)	TD	184
	filament	RT	93 80 82 } 89 }	TD	185
	filament	RT	~ 45-60	TD	186
				TD	187
				TD	188

TABLE VB
Heat of Adsorption of N₂ on Single Crystal Surfaces

Metal	Temperature	ΔH_{ads} (kcal/mole)	Technique	Ref.
Fe(100)	RT above	50 60 (58)	isotherm TD	189
Fe(111)	RT-	50	isotherm TD	190
Ir(100)	80 K	13-14(γ_3), 7-8(γ_1), 10-11(γ_2)	FEM	191
Mo(100)	78	9.7±1(γ) 87 ±3(β)	TD	87
Mo(110)	78	81±3(β)	TD	93
W(100)	78 ~1200-~1500 K	10.5(γ), 9.2(γ)+ 78.0(β_2)	TD	192
W(110) (100) (111)	100 K	<9(γ)	TD	179
	110 K	~10, ~11(γ +, γ -)	TD	
	300 K	75(β)		
	110 K	~9(γ)	TD	179
	220 K	16(α)		
	300 K	~75(β)		
W(110)	195, 300 K	79(β)	TD	193
W(110)	77, 300 K	117.6	FEM	178
W(100)	78	9.2 (γ) 10.5 (γ) 80 (β_2)	TD	87
W(100)	78-300 K	9-75	TD	179

Table References

1. F. Kelemen and A. Neda, Studia Univ. Babes-Bolyai, Ser. Math.-Phys. 17, 11 (1972).
2. V. E. Ostrovskii and M. F. Temkin, Kinet. i Katal. 7, 529 (1966).
3. W. Kollen and A. W. Czanderna, J. Colloid Interface Sci. 38, 152 (1972).
4. D. Brennan, D. O. Hayward and B. M. W. Trapnell, Proc. Roy. Soc. (London) A256, 81 (1960).
5. N. N. Dobrovolskii and V. E. Ostrovskii, Kinetics and Catalysis 12, 1324 (1972).
6. D. Brennan and M. J. Graham, Disc. Faraday Soc. 41, 95 (1966).
7. G.I. Murgulescu, G. Ilie and M. I. Vass, Rev. Roum. Chem. 14, 1201 (1969).
8. J. Bagg and F. C. Tompkins, Trans. Faraday Soc. 51, 1071 (1955).
9. G. Wedler, Z. Phys. Chem. N. F. 27, 388 (1961).
10. D. Brennan, D. O. Hayward and B. M. W. Trapnell, J. Phys. Chem. Solid 14, 117 (1960).
11. V. N. Ageev and N. I. Ionov, Soviet Physics-Technical Physics 16(10), / (1972).
1742
12. W. Greaves and R. E. Stickney, Surf. Sci. 11, 395 (1968).
13. P. A. Redhead, Can. J. Phys. 42, 886 (1964).
14. O. Beeck, Adv. Cat. 2, 151 (1951).
15. D. F. Klemperer and F. S. Stone, Proc. Roy. Soc. (London) A243, 375 (1957).
16. G. Wedler, Z. Phys. Chem. N. F. 24, 73 (1960).
17. B. Weber, J. Fusy and A. Cassuto, J. Chim. Phys. 66, 708 (1969).
18. Y. K. Peng and P. T. Dawson, Can. J. Chem. 52, 3507 (1974).
19. W. Weiershausen, Ann. Physik, Folge 7, 15, 150 (1965)

20. B. Weber, J. Fusy and A. Cassuto, *J. Chim. Phys. Phys.-Chim. Biol.* 73, 455 (1976).
21. J. K. Roberts, *Proc. Roy. Soc. (London)* A152, 464 (1935).
22. J. A. Becker, E. J. Becker and R. G. Brandes, *J. Appl. Phys.* 32, 411 (1961).
23. J. A. Becker, *Adv. Cat.* 7, 135 (1955).
24. Yu. G. Ptushinskii and B. A. Chuikov, *Surf. Sci.* 6, 42 (1967).
25. W. Engelmaier, R. E. Stickney, *Surf. Sci.* 11, 370 (1968).
26. H.-W. Wassmuth, H. Werner, and A. K. Mazumdar, *J. Vac. Sci. Tech.* 9, 835 (1972).
27. H. A. Engelhardt and D. Menzel, *Surf. Sci.* 57, 591 (1976).
28. G. Rovida, F. Ferroni, F. Maglietta and F. Pratesi, *Adsorption-Desorption Phenom., Proc. Int. Conf., 2nd, 1971 (Pub. 1972)*, p. 417. Ed. F. Ricca.
29. G. Rovida, F. Pratesi, M. Maglietta, and E. Ferroni, *J. Vac. Sci. Technol.* 9, 796 (1972).
30. G. Rovida, F. Pratesi, M. Maglietta, and E. Ferroni, *Surf. Sci.* 43, 230 (1974).
31. G. Ertl, *Surf. Sci.* 7, 309 (1967).
32. Yu. I. Belyakov and T. N. Kompaniets, *Sov. Phys.-Tech. Phys.* 17, 674 (1972).
33. W. H. Weinberg and W. F. Egelhoff Jr., *J. Vac. Tech. Technol.*
34. N. P. Vas'ko, Yu. G. Ptushinskii, and B. A. Chuikov, *Surf. Sci.* 14, 448 (1968).
35. G. Ertl and P. Rau, *Surf. Sci.* 15, 443 (1969).
36. G. Ertl and J. Koch, *Proc. Int. Cong. Catalysis, 5th, 1972 (Pub. 1973)*, p. 686. Ed. J. W. Hightower.
37. G. Kneringer and F. P. Netzer, *Surf. Sci.* 49, 125 (1975).
38. M. Bacal, J. L. Desplat and T. Alleau, *J. Vac. Sci. Tech.* 9, 851 (1972).

39. M. G. Wells and D. A. King, J. Phys. C7, 4053 (1974).
40. C. Kohrt and R. Gomer, J. Chem. Phys. 52, 3283 (1970).
41. Yu. P. Zingerman and V. A. Ishchuk, Sov. Phys.-Solid State 9, 623 (1967).
42. J. R. Anderson, Structure of Metallic Catalysts (Academic Press, New York) 1975.
43. O. Beeck, Rev. Mod. Phys. 17, 61 (1945).
44. M. D. Malev, Sov. Phys.-Tech. Phys. 17, 2009 (1973).
45. C. S. Alexander and J. Pritchard, J. Chem. Soc., Faraday Trans. I 68, 202 (1972).
46. J. Pritchard and F. C. Tompkins, Trans. Faraday Soc. 56, 540 (1960).
47. J. Lapujoulaude, K. S. Neil, J. Chem. Phys. 57, 3535 (1962).

48. O. Beeck, W. A. Cole and A. Wheeler, Disc. Faraday Soc. 8, 314 (1950).

49. A. S. Porter and F. C. Tompkins, Proc. Roy. Soc. (London) A217, 544 (1953).
50. E. Chornet and R. W. Coughlin, J. Cat. 27, 246 (1972); 28, 414 (1973).
51. V. J. Mimeaule and R. S. Hansen, J. Chem. Phys. 45, 2240 (1965).
52. R. I. Bickley and M. W. Roberts and W. C. Storey, J. Chem. Soc. 1971, 2774 (1971).
53. O. Beeck, Disc. Faraday Soc., 8, 118 (1950).

54. S. Černý, V. Ponec and L. Hládek, J. Cat. 5, 27 (1966).

55. R. A. Pasternak and N. Endow, J. Phys. Chem. 70, 4044 (1966).
56. D. Brennan and F. H. Hayes, Trans. Faraday Soc. 60, 589 (1964).
57. M. Wahba and C. Kemball, Trans. Faraday Soc. 49, 1351 (1953).
58. F. M. Bröcker and G. Wedler, Disc. Faraday Soc. 41, 87 (1966).
59. G. Wedler and F. M. Bröcker, Surf. Sci. 26, 454 (1971).
60. R. Gomer, Disc. J. Chem. Phys. 27, 1099 (1957).
61. R. Wortman, R. Gomer, R. Lundy, J. Chem. Phys. 27, 1099 (1957).
62. F. Sweet and E. Rideal, Proc. Int. Cong. Catalysis, 2nd Paris, 1960 (Pub. 1961).
63. P. M. Grundy and F. C. Tompkins, Trans. Faraday Soc. 53, 218 (1957).
64. C. M. Quinn and M. W. Roberts, Trans. Faraday Soc. 58, 569 (1962).
65. G. Wedler and G. Fisch, Ber. Kernforschungsanlage Juelich 1, 215 (1972).
66. D. D. Eley and P. R. Norton, Proc. Roy. Soc. (London) A314, 319 (1969).
67. A. W. Aldag and L. D. Schmidt, J. Cat. 22, 260 (1971).
68. J. J. Stephan, V. Ponec and W. M. H. Sachtler, J. Cat. 37, 81 (1975).
69. R. Lewis and R. Gomer, Surf. Sci. 17, 333 (1969).
70. M. Procop and J. Völter, Surf. Sci. 33, 69 (1972).
71. H. U. D. Wiesendanger, J. Cat. 2, 538 (1963).
72. W. J. M. Rootsmaert, L. L. van Reijen and W. M. H. Sachtler, J. Cat. 1, 416 (1962).
73. R. Ducros, J. J. Ehrhardt, M. Alnot and A. Cassuto, Surf. Sci. 55, 509 (1976).
74. S. M. Ko and L. D. Schmidt, Surf. Sci. 42, 508 (1974).
75. G. Wedler and H. Strothenk, Z. Phys. Chem. N. F. 48, 86 (1966).
76. G. Wedler and H. Strothenk, Ber. Bunsenges. Physk. Chem. 70, 214 (1966).
77. J. K. Roberts, Proc. Roy. Soc. (London) A152, 445 (1935).

78. J. K. Roberts and B. Whipp, Proc. Cambridge Phil. Soc. 30, 376 (1936).
79. T. W. Hickmott, J. Chem. Phys. 32, 810 (1960).
80. Yu. G. Ptushinskii and B. A. Chuikhov, Kinetics and Catalysis 5, 444 (1964).
81. G. E. Moore and F. C. Unterwald, J. Chem. Phys. 40(9), 2626 (1964).
82. R. Hansen, Exptl. Method of Cat. React. (Ed. R. B. Anderson).
83. L. J. Rigby, Can. J. Phys. 43, 1020 (1965).
84. R. Gomer, R. Wortman and R. Lundy, J. Chem. Phys. 26, 1147 (1957).
85. E. K. Rideal and B. M. W. Trapnell, J. Chem. Phys. 47, 126 (1950).
86. J. Pritchard, T. Catterick and R. K. Gupta, Surf. Sci. 53, 1 (1975).
87. H. R. Han and L. D. Schmidt, J. Phys. Chem. 75, 227 (1971).
88. M. Mahning and L. D. Schmidt, Z Phys. Chem. N. F. 80, 71 (1971).
89. J. Lapujoulade and K. S. Neil, Surf. Sci. 35, 288 (1973).
90. G. Ertl and D. Küppers, Ber. Bunsenges. Phys. Chem. 75, 1017 (1971).
91. J. Lapujoulade and K. S. Neil, J. Chim Phys. Phys-Chim. Biol. 70, 798 (1973); C. R. Acad. Sci. Paris, Ser. C 274, 2125 (1972).
92. L. H. Germer and A. U. MacRae, J. Chem. Phys. 37, 1382 (1962).
93. J. Lapujoulade, K. S. Neil, C. R. Acad. Sci. Paris Ser. C 274, 2125 (1972)
94. K. Christmann, O. Schober, G. Ertl and M. Neumann, J. Chem. Phys. 60, 4528 (1974).

95. J. McCarty, J. Falcona and R. J. Madix, *J. Cat.* 30, 235 (1973).
96. H. Conrad, G. Ertl and E. E. Latta, *Surf. Sci.* 41, 435 (1974).
97. F. P. Netzer and G. Kneringer, *Surf. Sci.* 51, 526 (1975).
98. W. H. Weinberg, *J. Vac. Sci. Technol.* 10, 89 (1973); Lampton, V. A., Ph.D. Thesis, Dept. Chem. Engineering, Univ. Calif., Berkeley, 1971.
99. K. Christmann, G. Ertl and T. Pignet, *Surf. Sci.* 54, 365 (1976).
100. W. H. Weinberg, D. R. Monroe, V. Lampton and R. P. Merrill, *J. Vac. Sci. Tech.* 14, 444 (1977).
101. D. L. Fehrs and R. E. Stickney, *Surf. Sci.* 8, 267 (1967).
102. P. W. Tamm and L. D. Schmidt, *J. Chem. Phys.* 51, 5352 (1969); P. J. Estrup and J. Anderson, *J. Chem. Phys.* 45, 2254 (1966).
103. P. W. Tamm and L. D. Schmidt, *J. Chem. Phys.* 54, 4775 (1971) ; K. J. Matysik, *Surf. Sci.* 29, 324 (1972).
104. R. R. Rye, B. D. Barford and P. G. Cartier, *J. Chem. Phys.* 59, 1693 (1973).
105. N. N. Kartaradage and N. P. Sokolova, *Doklady Physical Chemistry* (Proc. Acad. Sci. USSR, Phys. Chem Sect.) 172, 39 (1967).
106. B. M. W. Trapnell, *Proc. Roy. Soc. (London)* A218, 566 (1953).
107. D. Brennan and F. M. Hayes, *Phil. Trans. Roy. Soc. (London)* A258, 347 (1965).
108. J. Bagg and F. C. Tompkins, *Trans. Faraday Soc.* 51, 107 (1955).

109. Ch. Kleint and W. Moldenhauer, Trans. Int. Vac. Congr. 3rd, Stuttgart, 1965 (Pub. 1966).
110. D. A. Degras, J. Lecante, J. Chim. Phys. Phys.-Chim. Biol. 64, 405 (1967).
111. P. A. Redhead, Appl. Phys. Lett. 4, 166 (1964).
112. A. D. Crowell and L. D. Matthews, Surf. Sci. 7, 79 (1967).
113. O. Beeck, W. A. Cole and W. Wheeler, Disc. Faraday Soc. 8, 314 (1950).
114. G. Wedler and G. Schroll, Z. Phys. Chem. N. F. 85, 216 (1973).
115. M. McD. Baker and E. K. Rideal, Trans. Faraday Soc. 51, 1597 (1955).
116. N. Nayasaki, J. Watanabe and K. Kawasaki, Denki. Gijutsu. Sogo. Kenkyujo, Ih. 36, 1576 (1960).
117. A. D. Crowell, J. Chem. Phys. 32, 1576 (1960).
118. A. M. Hogan and D. A. King, The Structure and Chemistry of Solids (Ed. G. A. Somorjai) 57-I (1969).
119. Y. Nishiyama and H. Wise, J. Cat. 32, 50 (1974); P. A. Redhead, Vacuum 12, 203 (1962).
120. R. P. H. Gasser, R. Thwaites and J. Wilkinson, Trans. Faraday Soc. 63, 195 (1967).
121. M. Alnot, J. J. Ehrhardt, J. Fusy and A. Cassuto, Surf. Sci. 46, 81 (1974).
122. J. T. Yates, Jr., and T. E. Madey, J. Chem. Phys. 51, 334 (1969)
123. G. Ehrlich, J. Chem. Phys. 36, 1171 (1962).
124. G. Ehrlich, J. Chem. Phys. 34, 39 (1961).

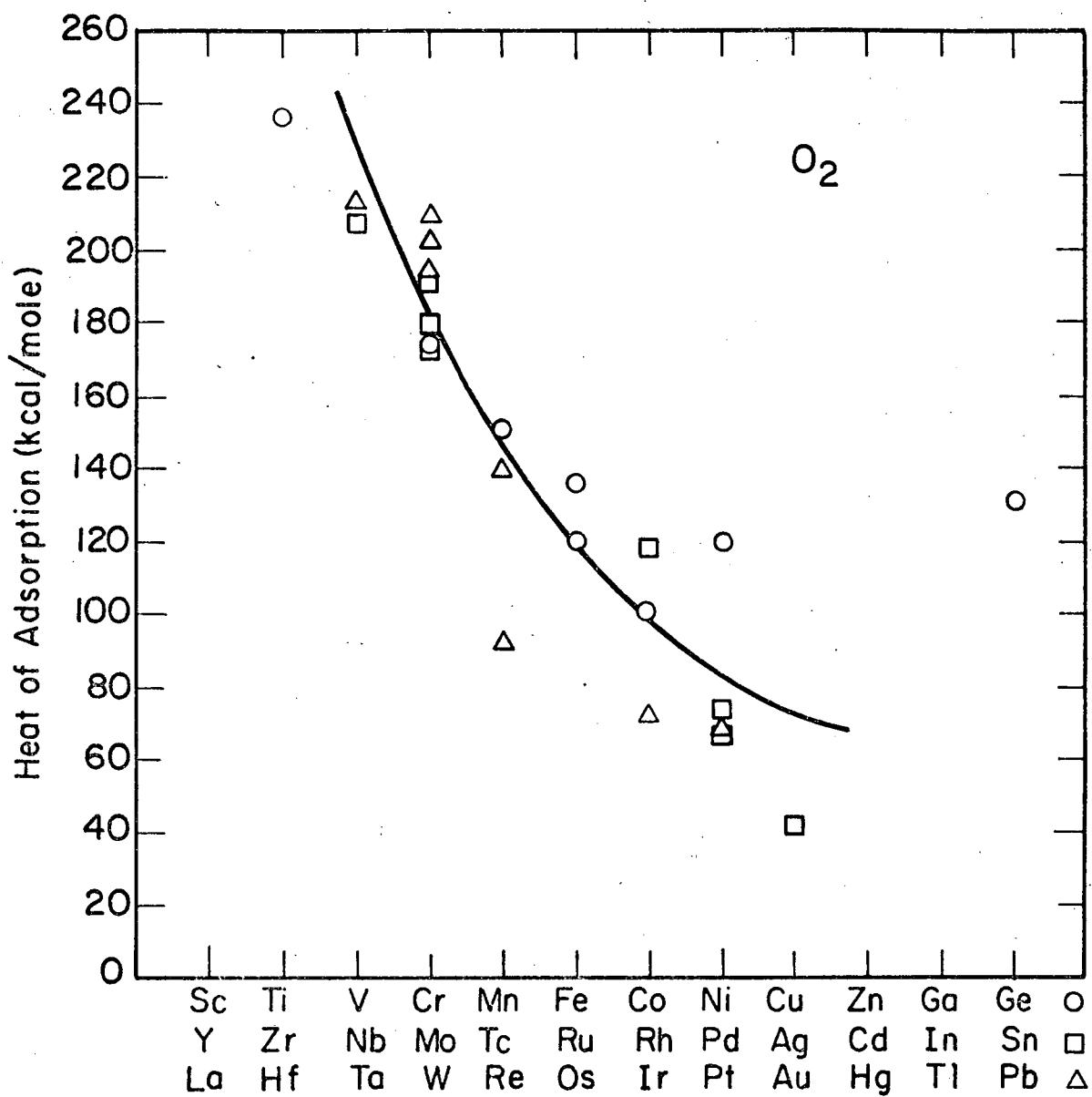
125. D. A. Degras, *Nuovo Cimento Suppl.* 5, 408 (1967).
126. P. A. Redhead, *Trans. Faraday Soc.* 57, 641 (1961).
127. L. J. Rigby, *Can. J. Phys.* 42, 1256 (1964); 43, 532 (1964).
128. L. W. Swanson and R. Gomer, *J. Chem. Phys.* 39, 2813 (1963).
129. R. Klein, *J. Chem. Phys.* 31, 1306 (1959).
130. E. K. Rideal and B. M. W. Trapnell, *Proc. Roy. Soc. (London)* A205, 409 (1951).
131. Yu. K. Ustinov, V. N. Ageev and N. I. Ionov, *Sov. Phys.-Tech. Phys.* 10, 851 (1965).
132. G. McElhiney, H. Papp, J. Pritchard, *Surf. Sci.* 54, 617 (1976).
133. D. A. Degras, *Nuovo Cimento, Suppl.* 5, 420 (1967).
134. J. Lapujoulade, *Nuovo Cimento, Suppl.* 5, 433 (1967).
135. M. A. Chesters, J. Pritchard and M. L. Sims, *Int. Symp. Adsorption-Desorption Phenomena*, 2nd, Florence, April 1971.
136. J. C. Tracy, *J. Chem. Phys.* 56, 2736, 2748 (1972).
137. H. Papp and J. Pritchard, *Surf. Sci.* 53, 371 (1975).
138. J. E. Demuth and T. N. Rhodin, *Surf. Sci.* 45, 249 (1974); K. Christmann and G. Ertl, *Z. Naturforsch.* 28A, 1144 (1973).
139. C. M. Comrie and W. H. Weinberg, *J. Chem. Phys.* 64, 250 (1976).
140. D. I. Hagen, B. E. Nieuwenhuys, G. Rovida and G. A. Somorjai, *Surf. Sci.* 57, 632 (1976); 59, 177 (1976).
141. V. N. Ageev and N. I. Ionov, *Kinetics and Catalysis* 14, 592 (1973).
142. K. Kleier, A. C. Zettlemoyer and H. Leidheiser, Jr., *J. Chem. Phys.* 52, 589 (1970).

143. H. H. Madden, J. Kuppers and G. Ertl, *J. Chem. Phys.* 58, 3401 (1973).
144. T. N. Taylor, P. J. Estrup, *J. Vac. Sci. Tech.* 10, 26 (1973).
145. J. M. McCarty and R. J. Madix, *Surf. Sci.* 54, 121 (1976).
146. C. R. Helms and R. J. Madix, *Surf. Sci.* 52, 677 (1975).
147. J. L. Falconer and R. J. Madix, *Surf. Sci.* 48, 393 (1975).
148. K. Christmann, O. Schober and G. Ertl, *J. Chem. Phys.* 60, 4719 (1974).
149. Y. Viswanath and L. D. Schmidt, *J. Chem. Phys.* 59, 4184 (1973).
150. L. D. Mattew, *Surf. Sci.* 24, 248 (1971).
151. J. C. Tracy and P. W. Palmberg, *J. Chem. Phys.* 51, 4852 (1969).
152. H. Conrad, G. Ertl and E. E. Latta, *Surf. Sci.* 43, 462 (1974).
153. G. Ertl and J. Koch, *Z. Naturforsch.* 25A, 1906 (1970); G. Ertl and J. Koch, *Adsorption and Desorption Phenomena* (Ed. F. Ricca) Academic Press, 1972, p. 345.
154. G. Ertl and J. Koch, *Z. Phys. Chem. N. F.* 69, 323 (1970).
155. G. Ertl and P. Rau, *Surf. Sci.* 15, 443 (1969).
156. R. Lewis and R. Gomer, *Nuovo Cimento* 5, 506 (1967).

157. C. M. Comrie and R. M. Lambert, *J. C. S. Faraday I.* 72, 1659 (1976).
158. H. P. Bonzel and R. Ku, *J. Chem. Phys.* 58, 4617 (1973).
159. R. A. Shigeishi and D. A. King, *Surf. Sci.* 58, 379 (1976).
160. T. E. Madey, D. Menzel, *Proc. Int. Conf. Solid Surf.*, 2nd, 1974, (Pub. 1974) 229-35. Ed. H. Kumagai, T. Toya.
161. P. D. Reed, C. M. Comrie and R. M. Lambert, *Surf. Sci.* 59, 33 (1976).
162. L. R. Clavenna and L. D. Schmidt, *Surf. Sci.* 33, 11 (1972).

163. C. Kohrt and R. Gomer, Surf. Sci. 24, 77 (1971); 40, 71 (1973).
164. V. S. Ageikin, Yu. G. Ptushinskii, Sov. Phys.-Solid State 10, 1698 (1969).
165. D. Brennan and D. O. Hayward, Phil. Trans. Roy. Soc. (London) A258, 375 (1965).
166. G. Wedler, D. Borgmann and K.-P. Geuss, Surf. Sci. 47, 592 (1975).
167. D. A. King, Surf. Sci. 9, 375 (1968).
168. S. M. Ko and L. D. Schmidt, Surf. Sci. 42, 508 (1974).
169. V. J. Mimeault and R. S. Hanson, J. Phys. Chem. 70, 3001 (1966).
170. T. Oguri, J. Phys. Soc. Japan 19, 77 (1964).
171. A. A. Parry and J. A. Pryde, Brit. J. Appl. Phys. 18, 329 (1967).
172. D. A. King and F. C. Tompkins, Trans. Faraday Soc. 64, 496 (1968).
173. P. Kisliuk, J. Chem. Phys. 31, 1605 (1959).
174. P. Kisliuk, J. Chem. Phys. 30, 174 (1959).
175. G. Ehrlich, J. Chem. Phys. 34, 29 (1961).
176. D. O. Hayward, D. A. King and F. C. Tompkins, Proc. Roy. Soc. A297, 305 (1967).
177. G. Ehrlich and F. G. Hudda, J. Chem. Phys. 32, 942 (1960).
178. G. Ehrlich and F. G. Hudda, J. Chem. Phys. 36, 3233 (1962).
179. T. A. Delchar and G. Ehrlich, J. Chem. Phys. 42, 2686 (1965).
180. G. Ehrlich, Adv. in Cat. 14, 255 (1963); J. Chem. Phys. 36, 1171 (1962).
181. T. W. Hickmott and G. Ehrlich, J. Phys. Chem. Solid 5, 47 (1958).
182. G. Ehrlich and T. W. Hickmott, J. Chem. Phys. 26, 219 (1957).
183. G. Ehrlich, J. Phys. Chem. 60, 1388 (1956); O. Beeck, Advances in Catalysis 2, 151 (1950).
184. J. A. Becker and C. D. Hartman, J. Phys. Chem. 153, 159 (1953).

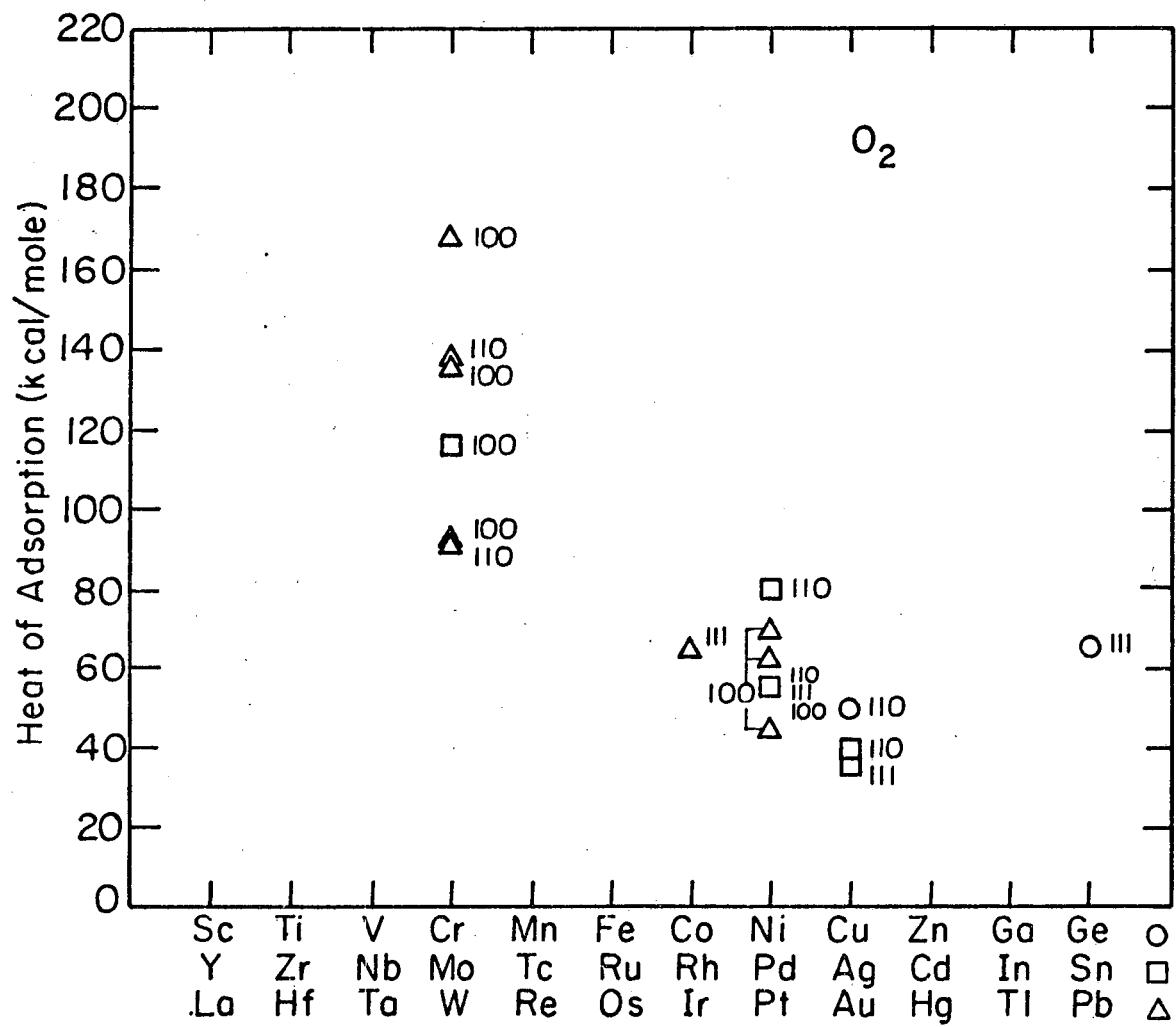
185. T. Oguri, J. Phys. Soc. Japan 18, 1280 (1963).
186. M. P. Hill, S. M. A. Lecchini and B. A. Pethica, Trans. Faraday Soc. 62, 229 (1966).
187. T. E. Madey and J. T. Yates, Jr., J. Chem. Phys. 44, 1675 (1966).
188. H. F. Winters and D. E. Horne, Surf. Sci. 24, 587 (1971).
189. G. Ertl, M. Grunze and M. Weiss, J. Vac. Sci. Technol. 13, 314 (1976).
190. G. Ertl, M. Grunze and M. Weiss, private communication.
191. B. E. Nieuwenhuys, D. Th. Meijer and W. M. H. Sachtler, Surf. Sci. 40, 125 (1973).
192. L. R. Clavenna and L. D. Schmidt, Surf. Sci. 22, 365 (1970).
193. P. W. Tamm and L. D. Schmidt, Surf. Sci. 26, 286 (1971).
194. J. C. P. Mignolet, J. Chim. Phys. Phys.-Chim. Biol. 54, 19 (1957).
195. T. Oguri, J. Phys. Soc. Japan 18, 1280 (1963).



XBL773-5235

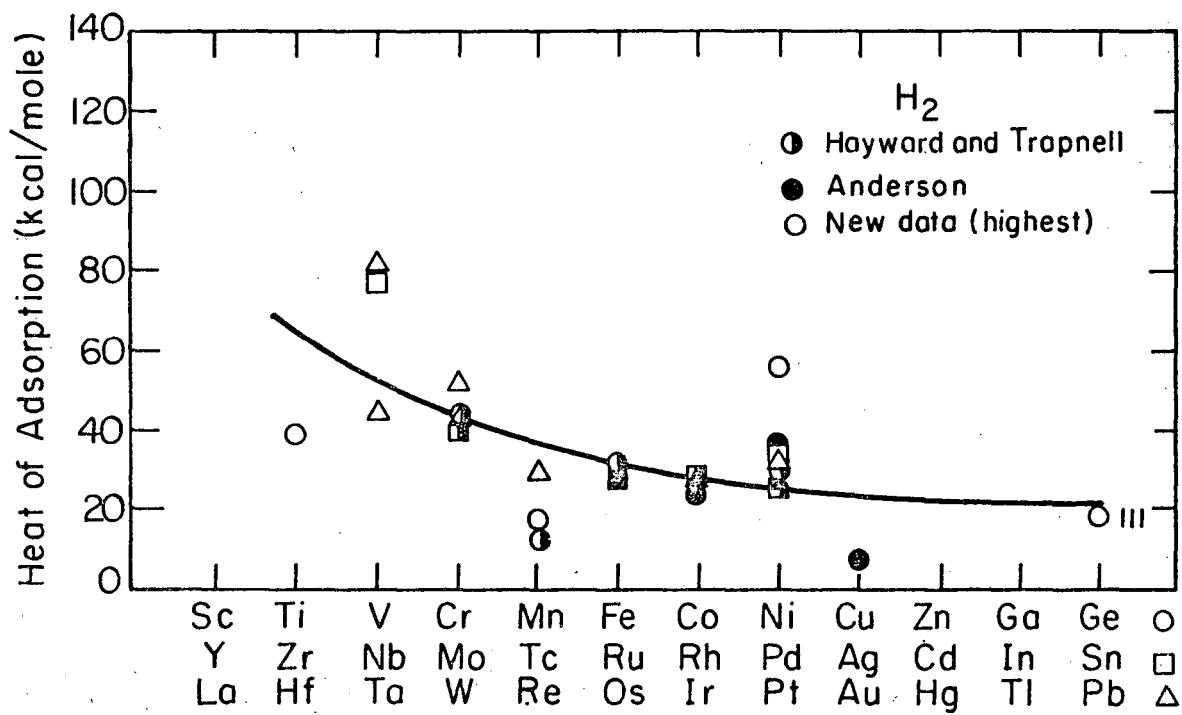
Fig. 1a

0 0 0 0 4 8 0 5 9 4 9
-49-



XBL 777- 5698

Fig. 1b



XBL 777~5700

Fig. 2a

0 0 0 0 4 8 0 5 9 5 0
-51-

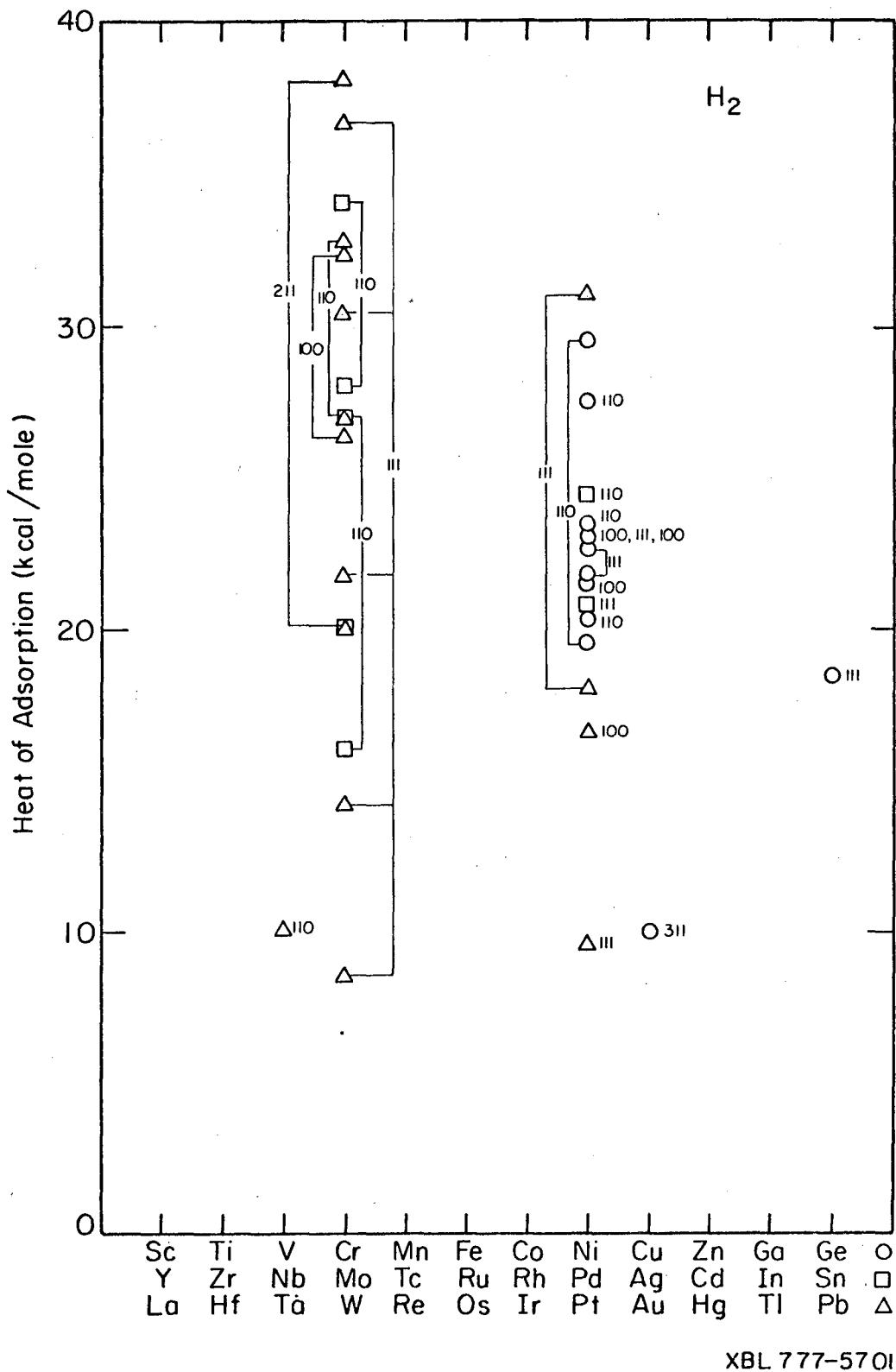
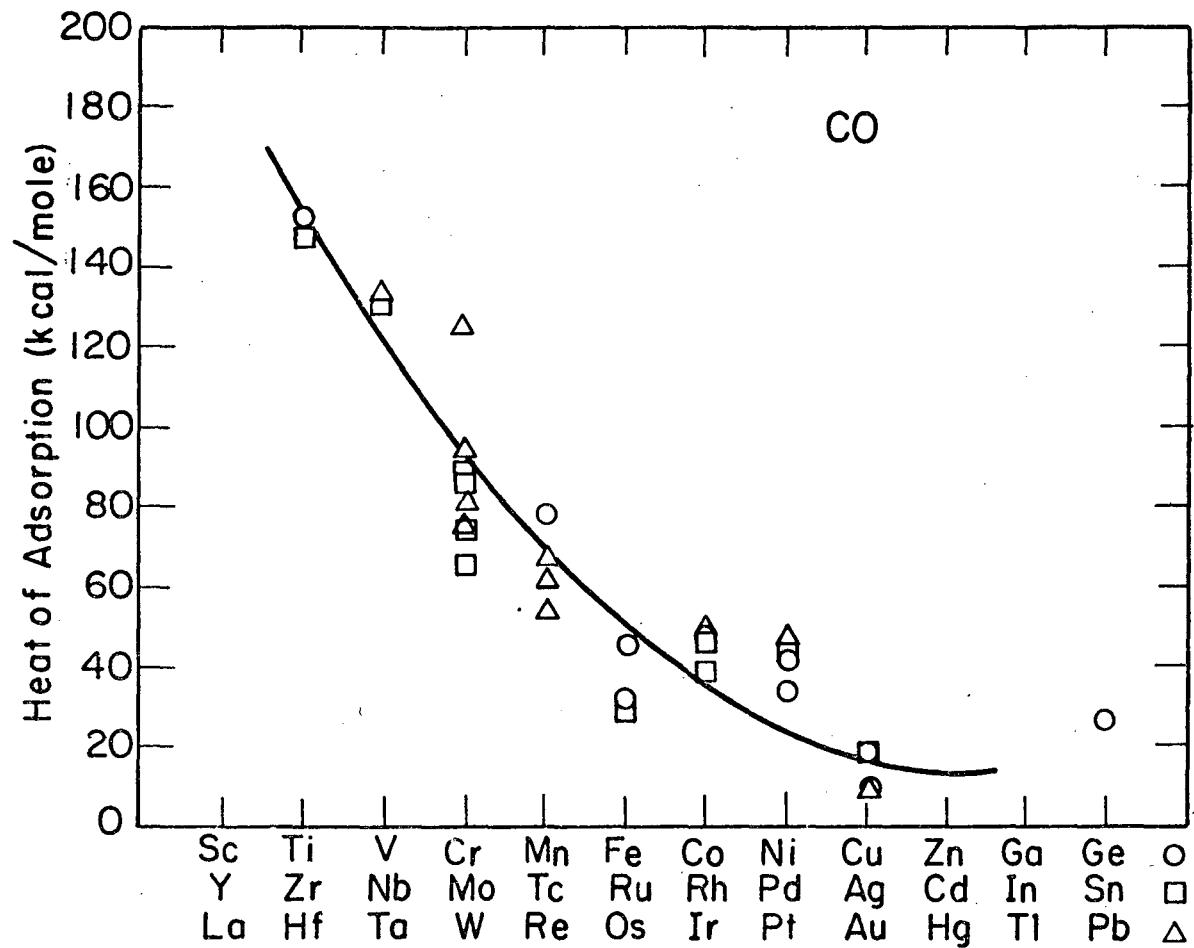
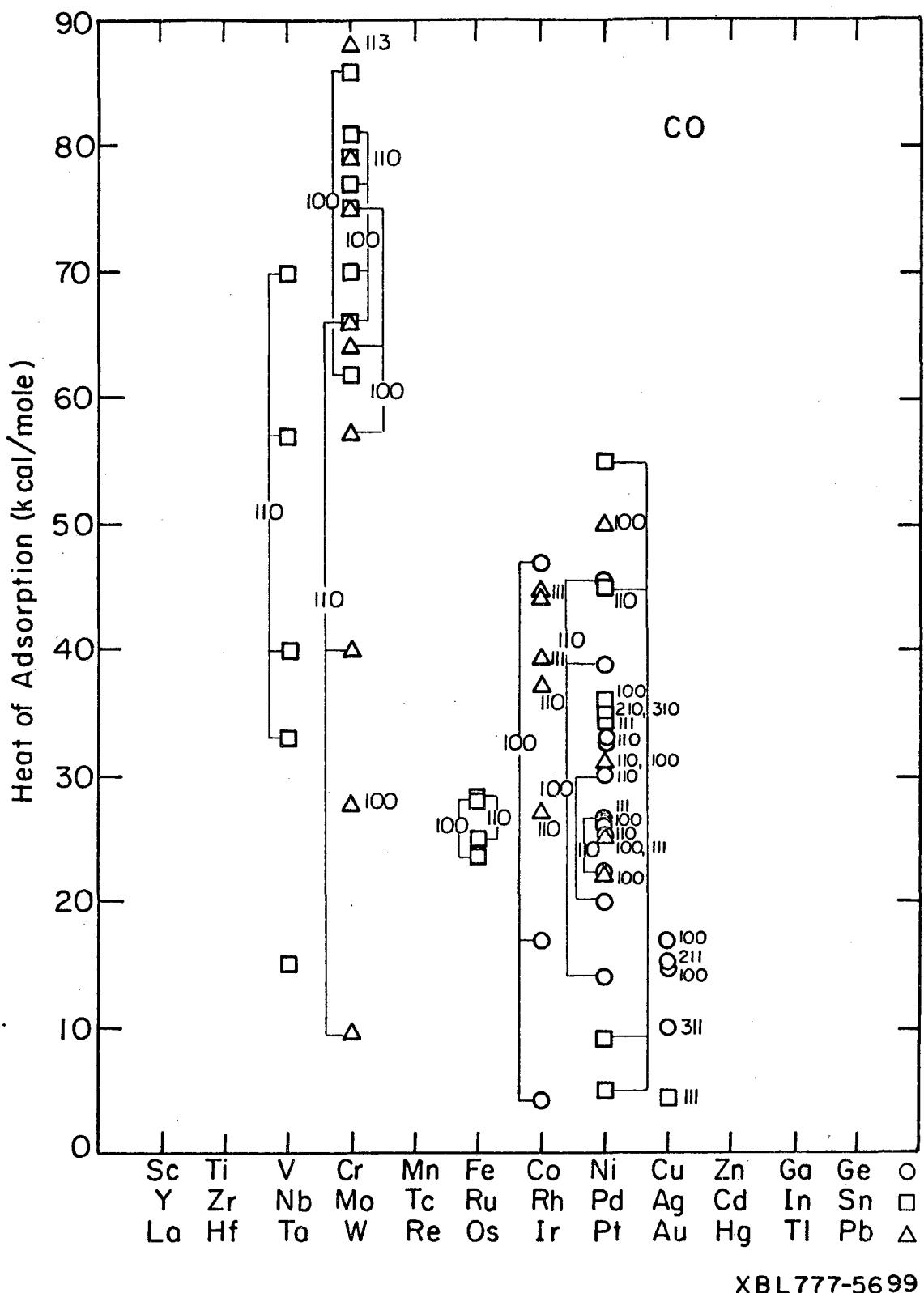


Fig. 2b



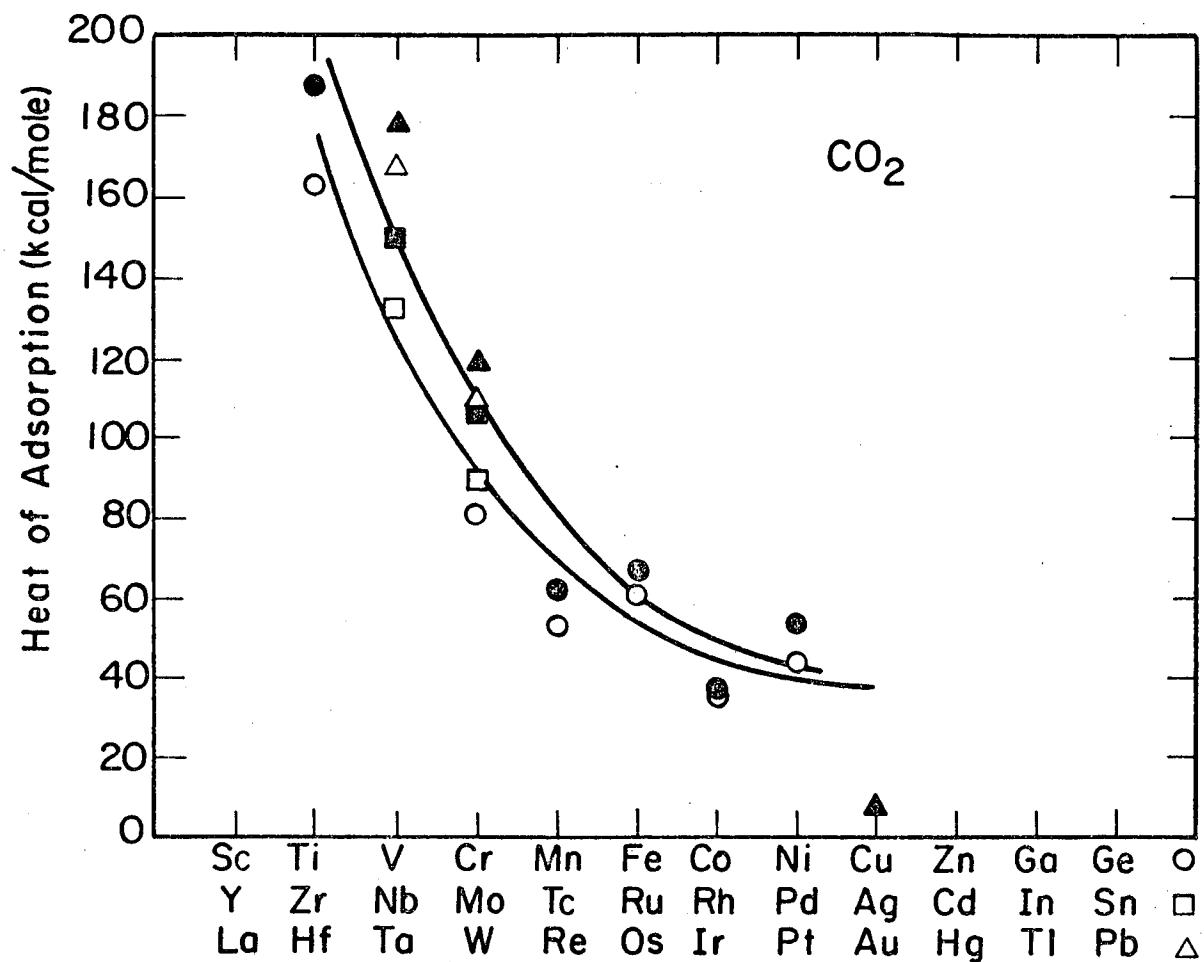
XBL 773-5236

Fig. 3a



XBL777-5699

Fig. 3b



XBL773-5234

Fig. 4

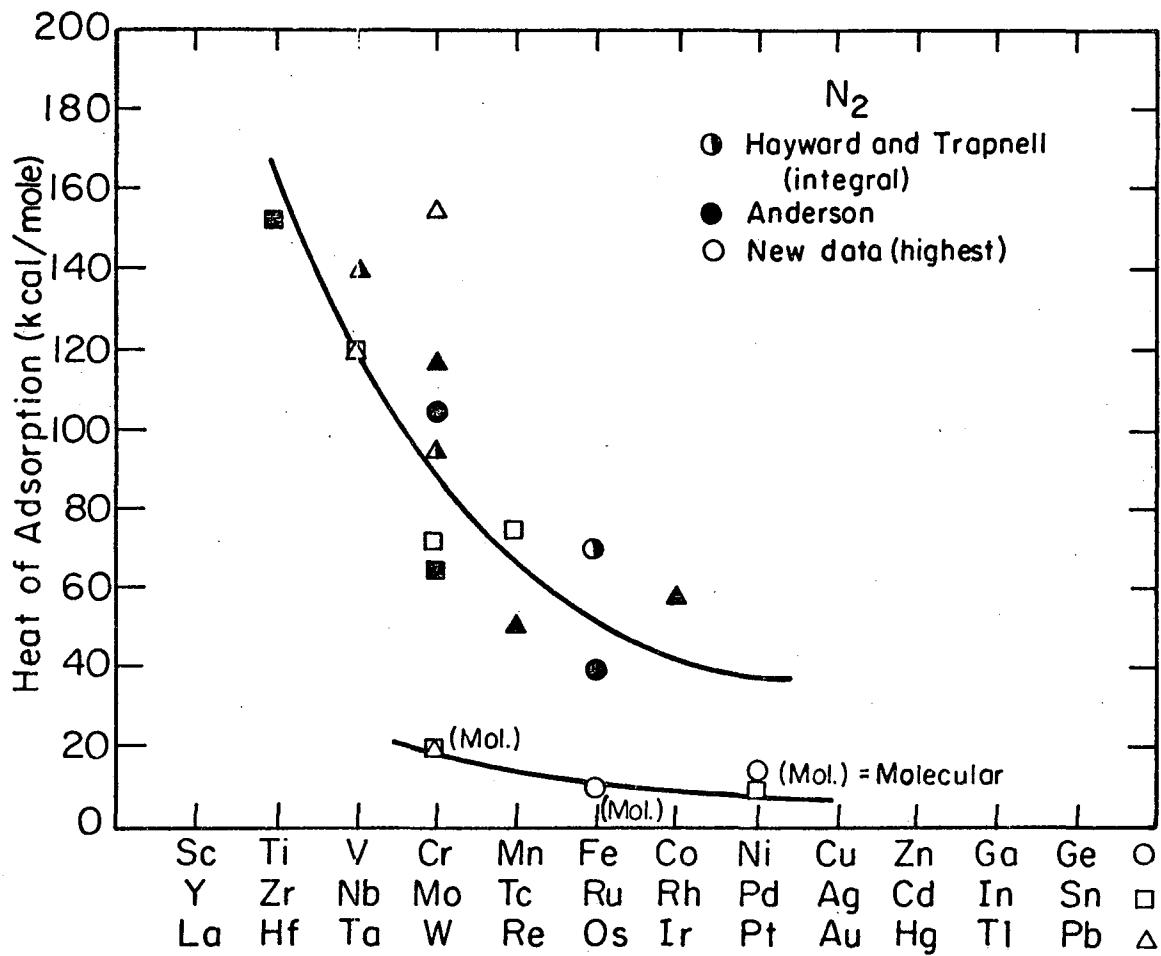
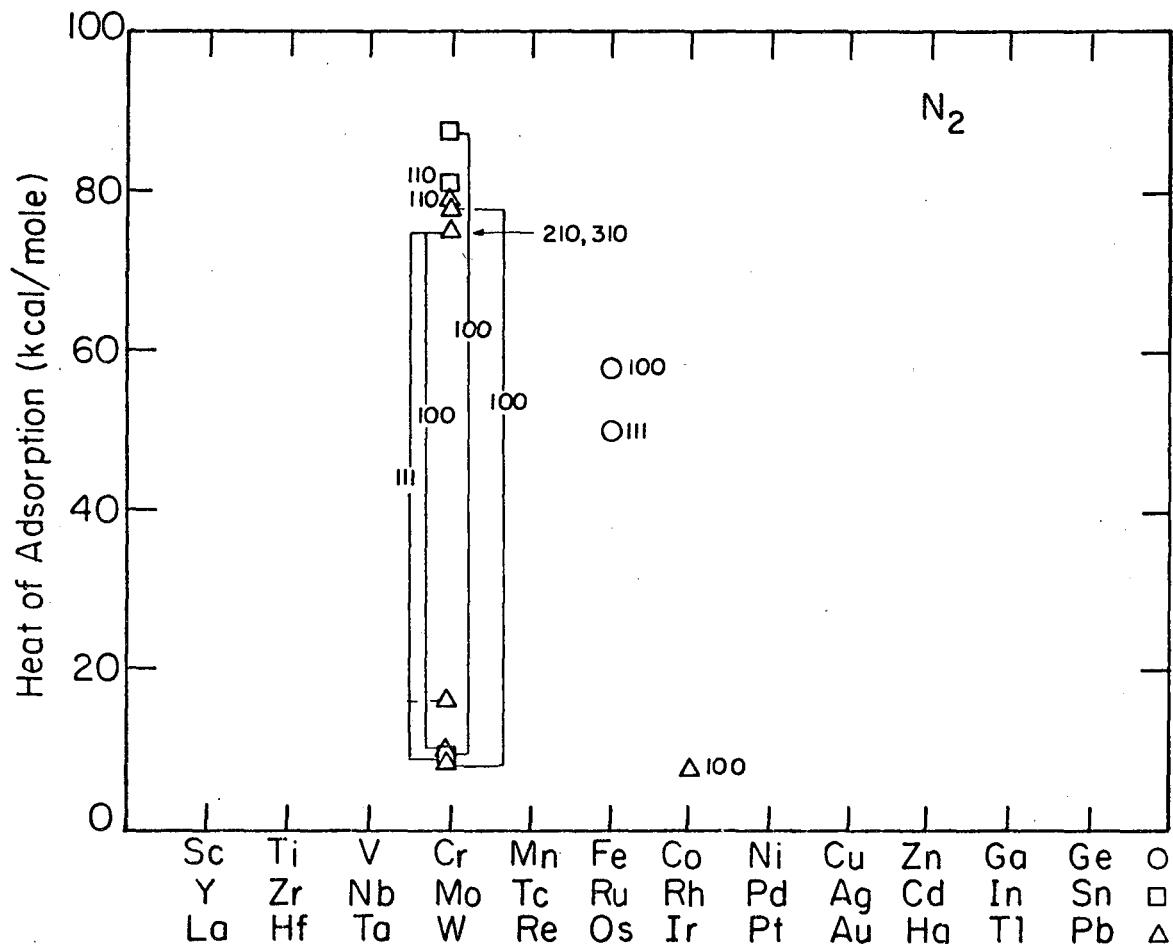
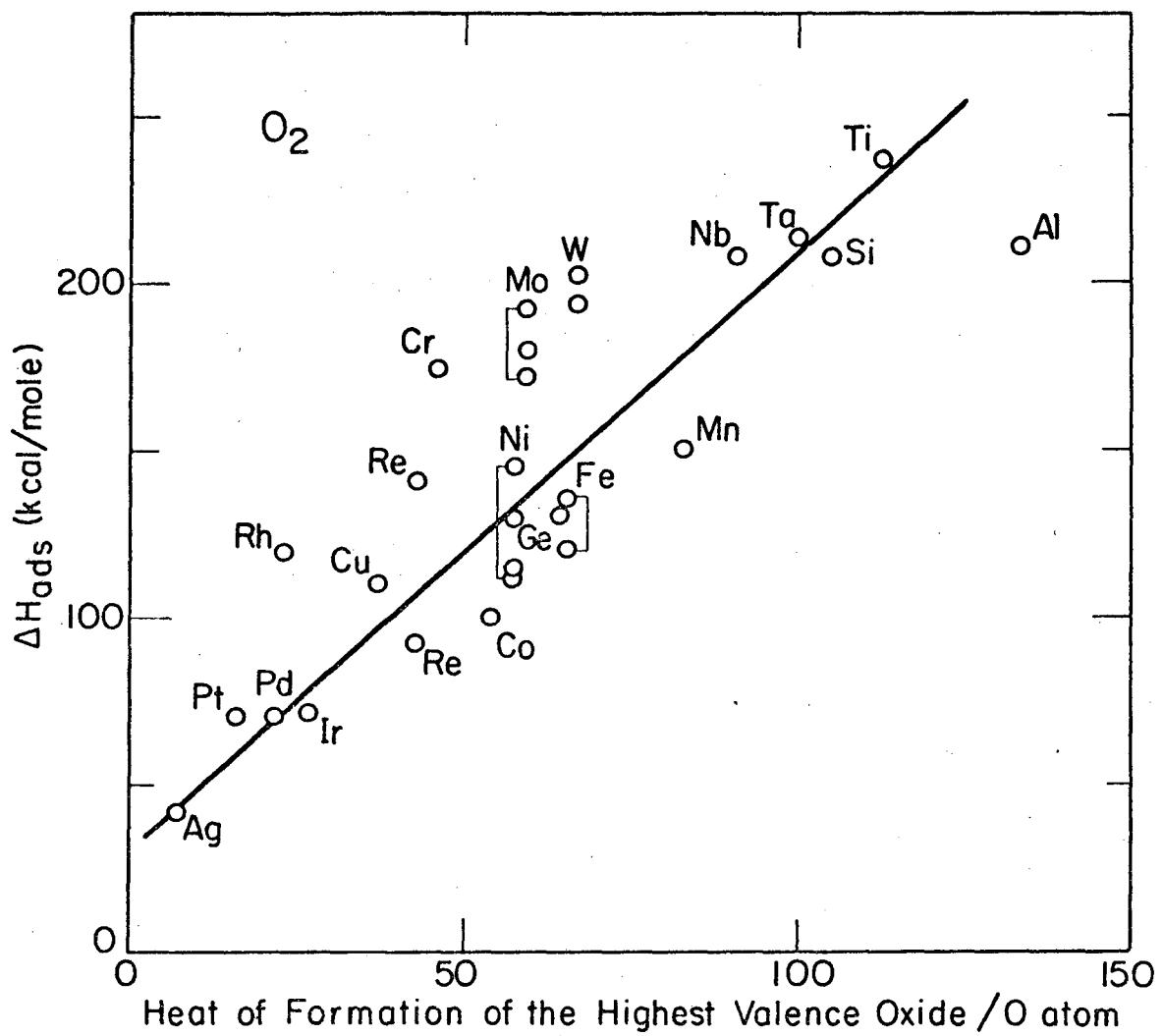


Fig. 5a



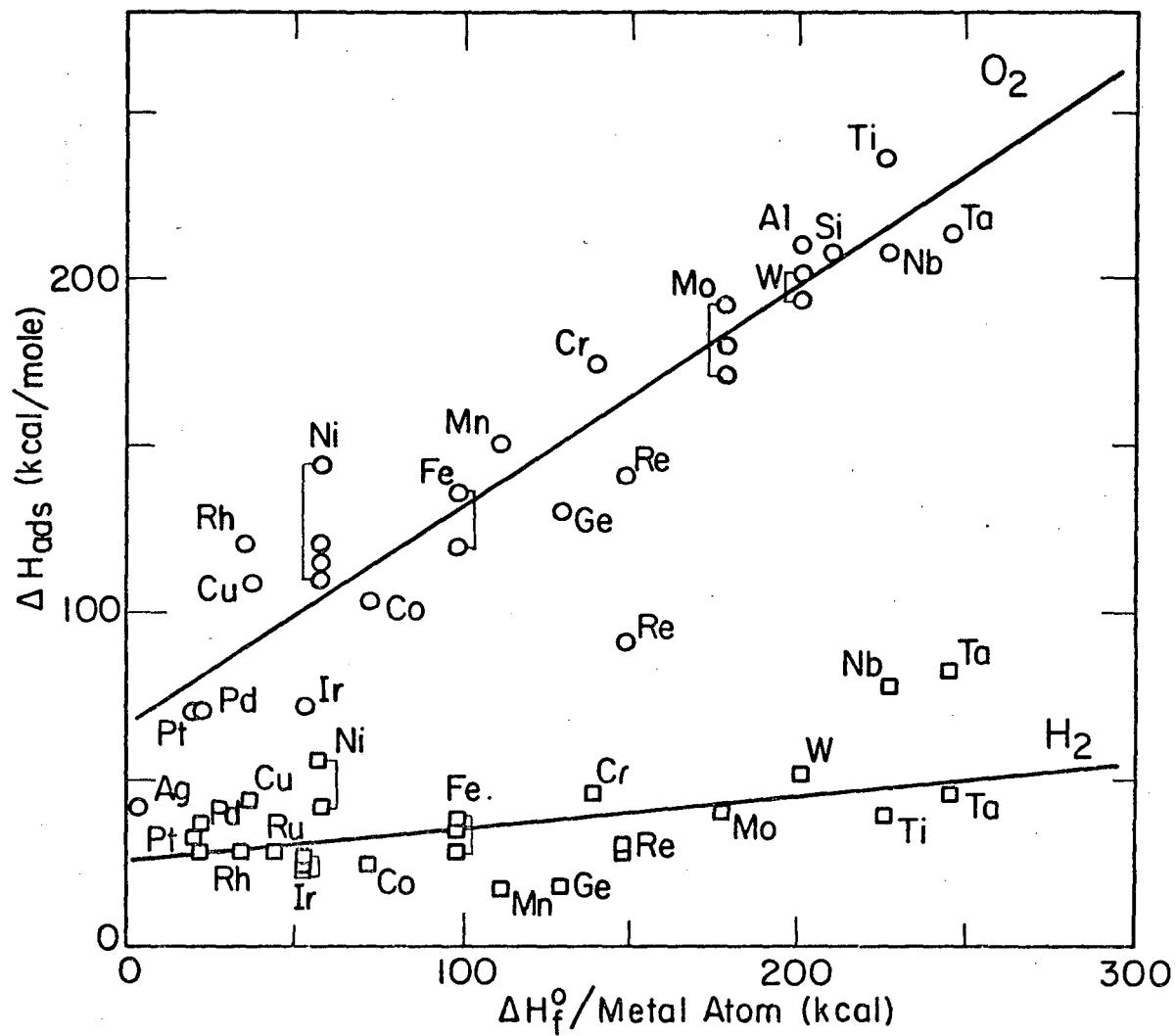
XBL 777-5703

Fig. 5b



XBL 773- 5232

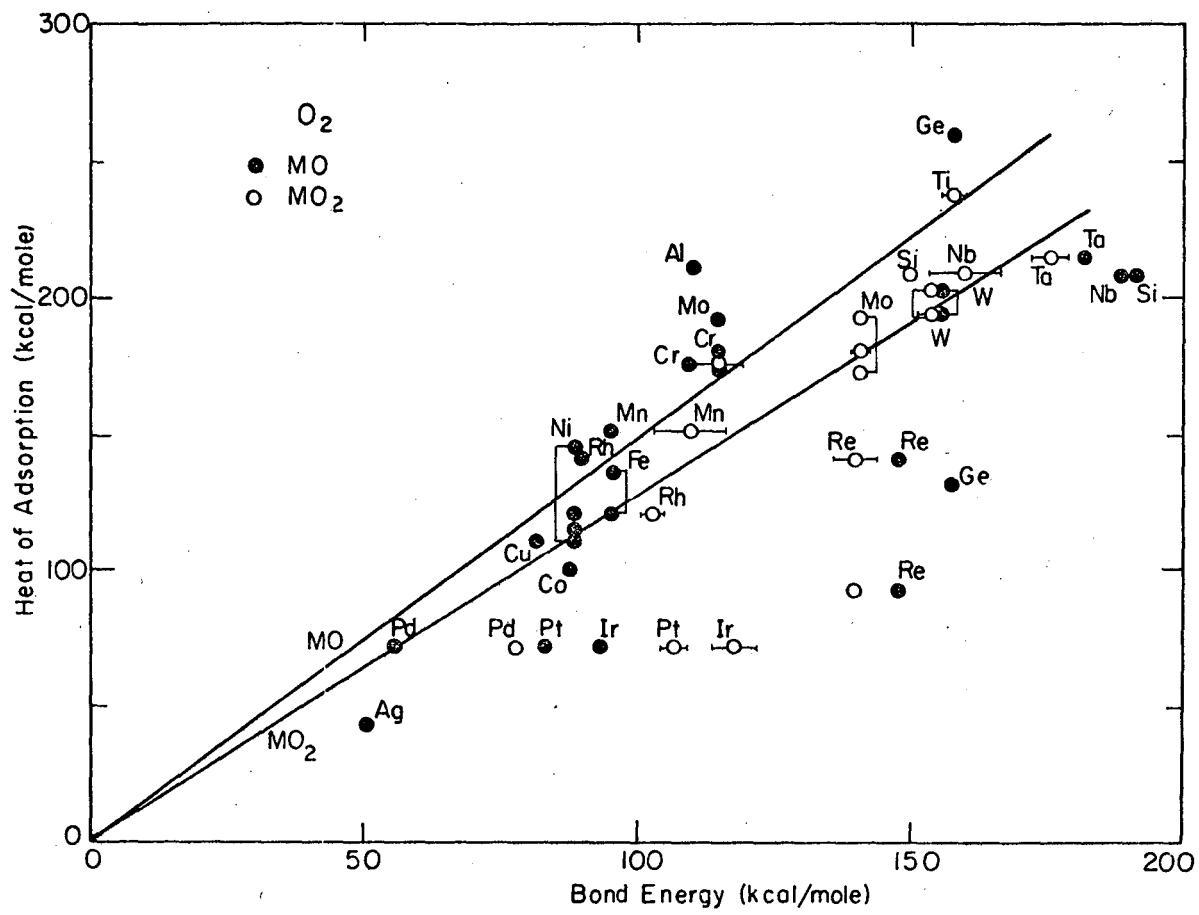
Fig. 6



XBL 773-5233

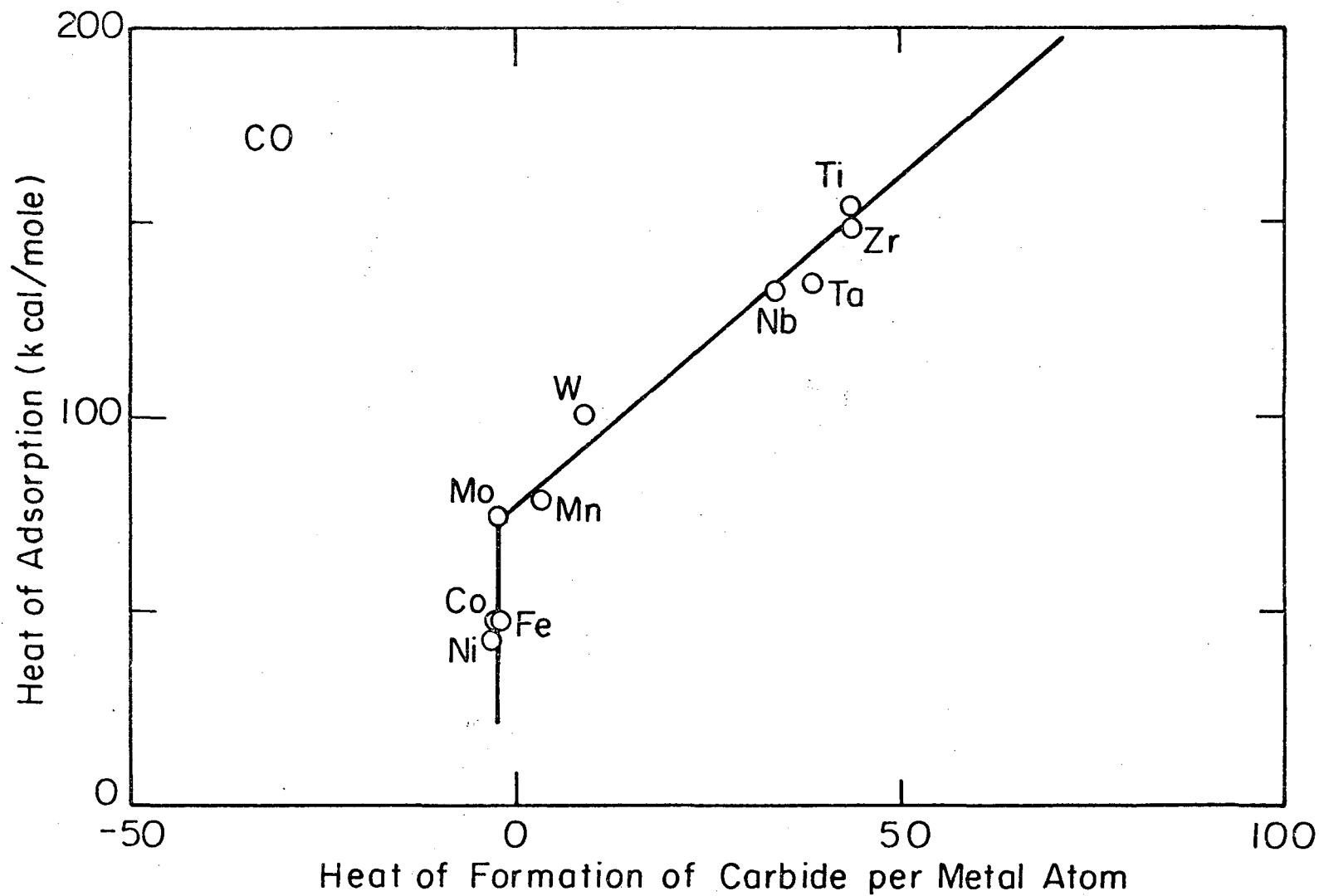
Fig. 7

0 0 1 0 4 8 0 5 9 5 2
-59-



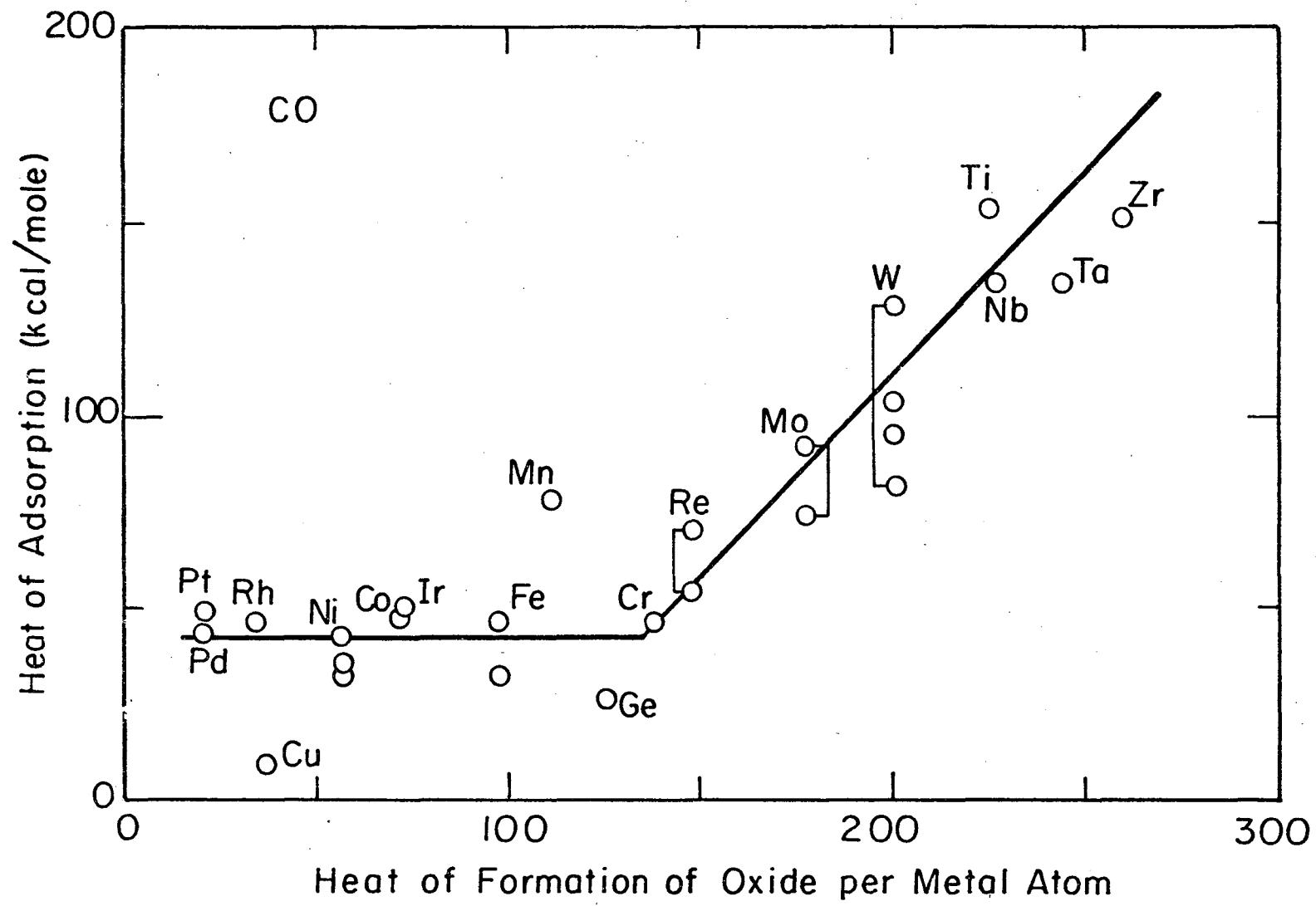
XBL7 77-5704

Fig. 8



XBL777-5705

Fig. 9



XBL777-5706

Fig. 10

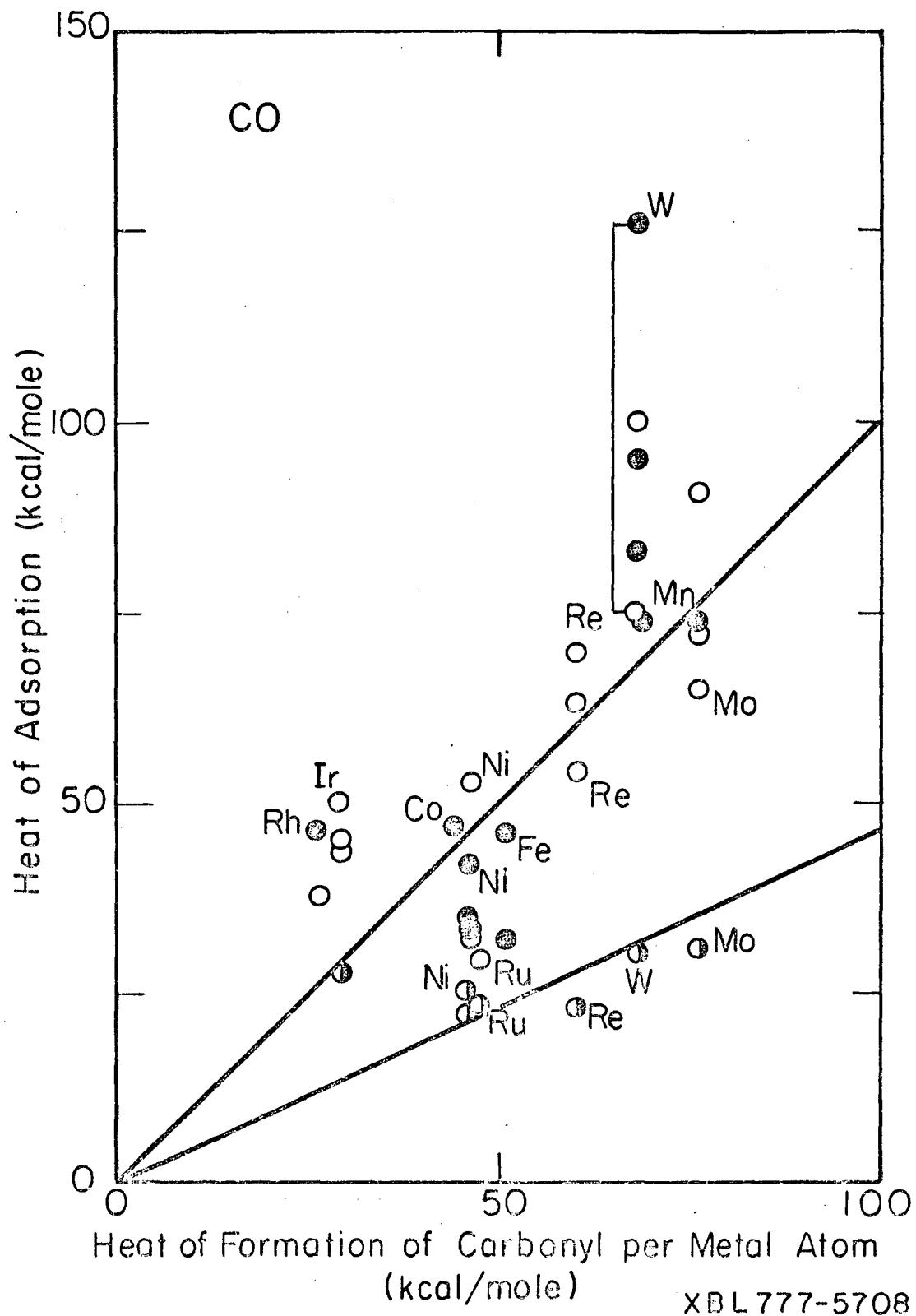


Fig. 11

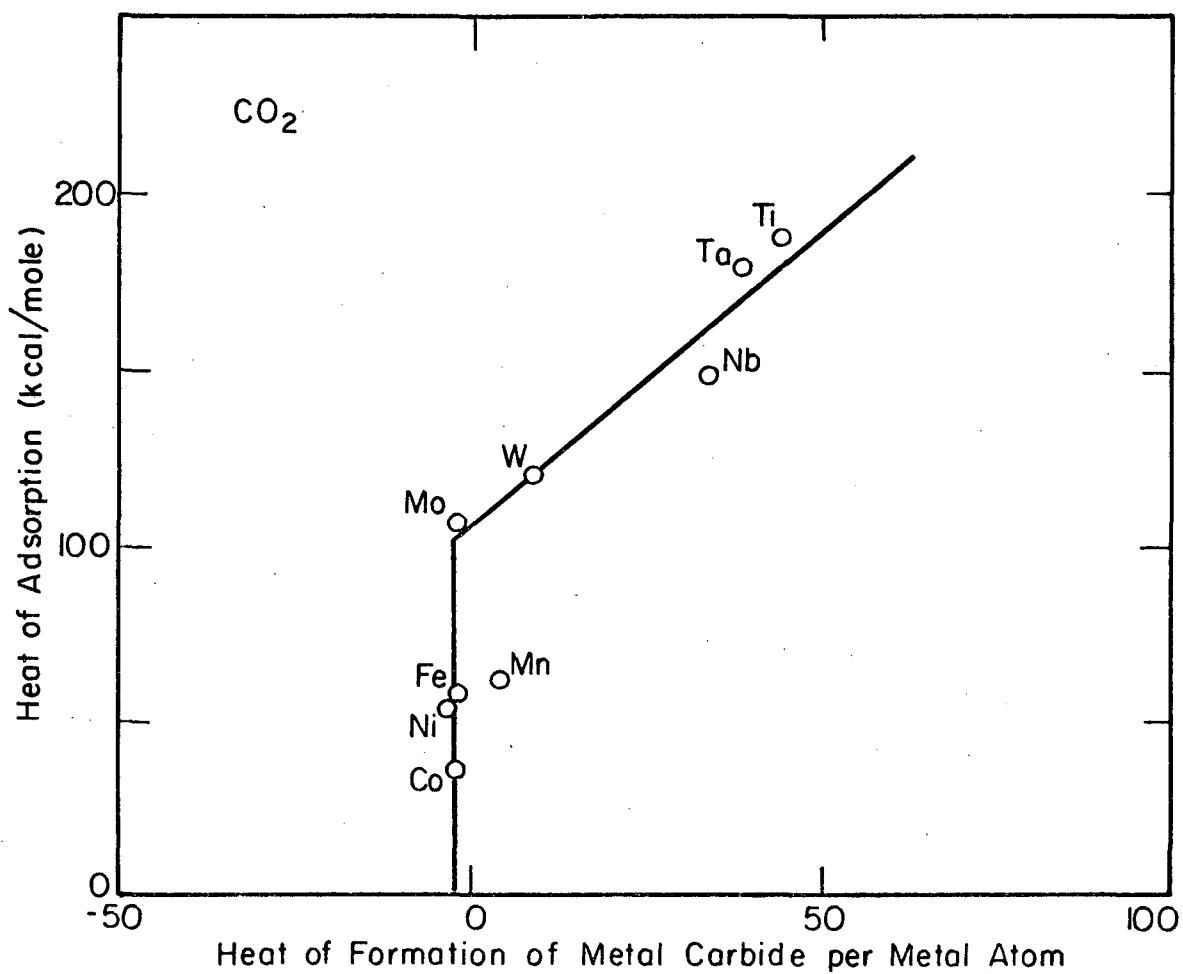
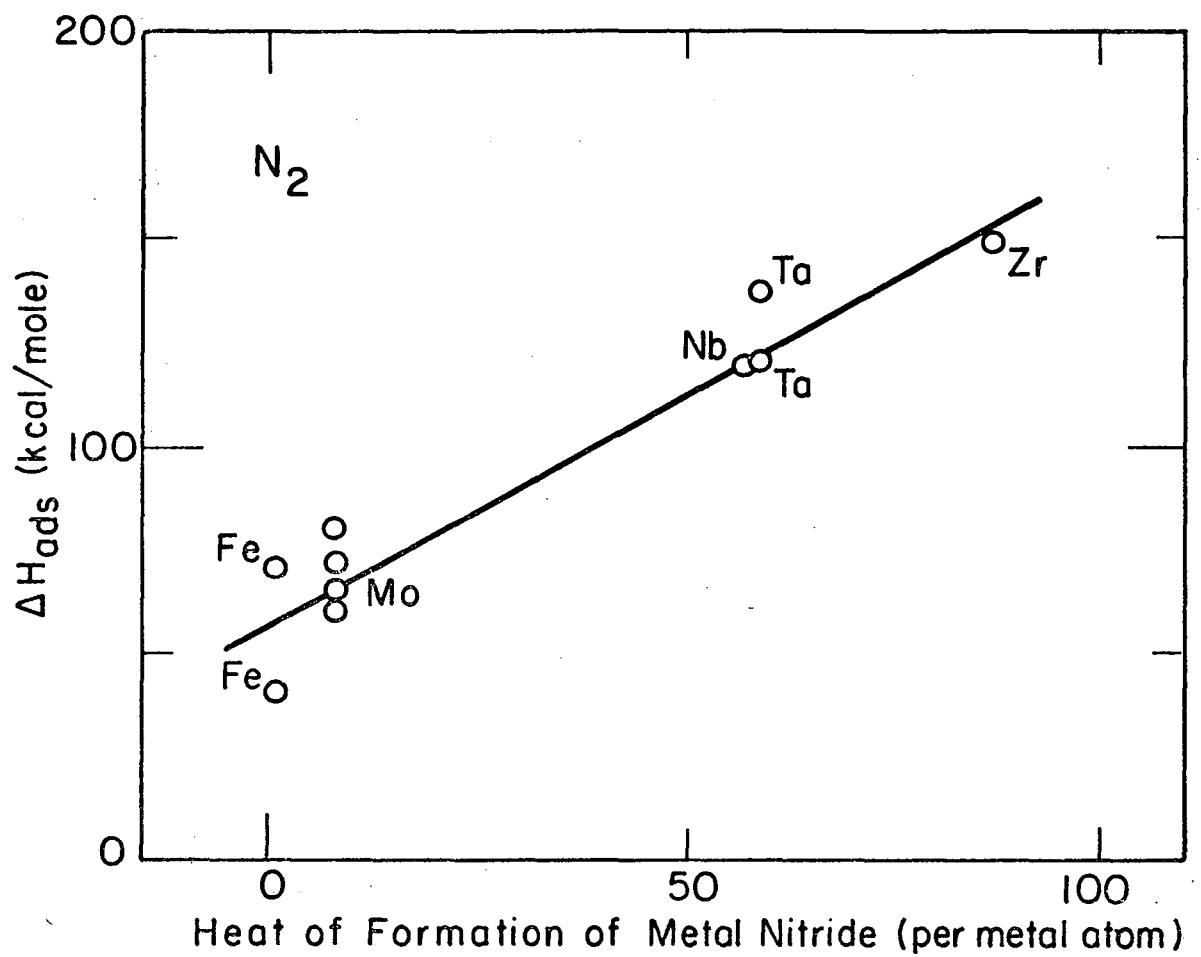


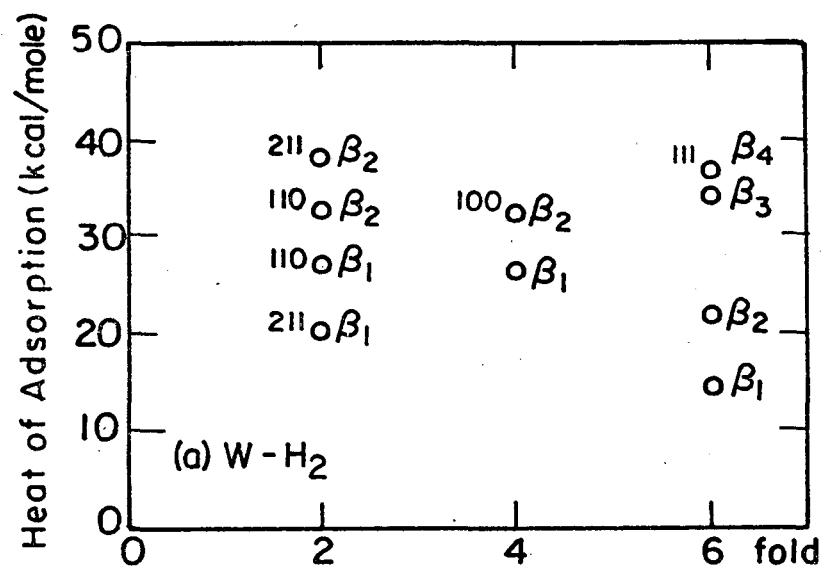
Fig. 12

XBL 777-5707

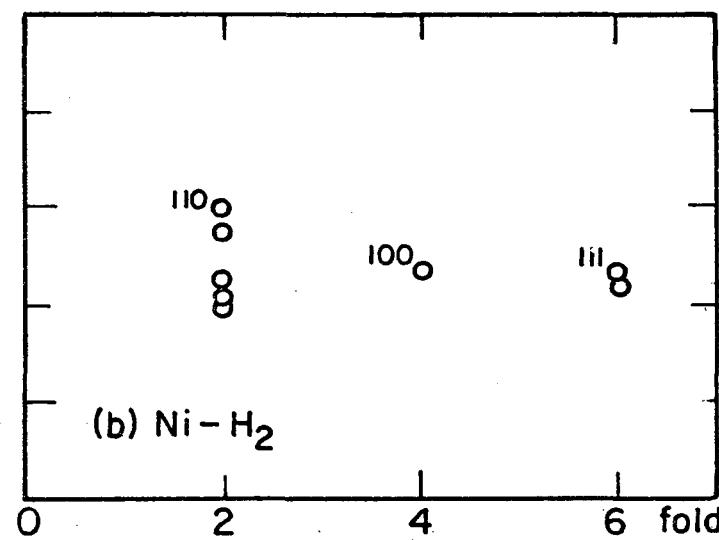


XBL 773-5231

Fig. 13



(a) W - H₂



(b) Ni - H₂

XBL777-5710

Fig. 14a

Fig. 14b

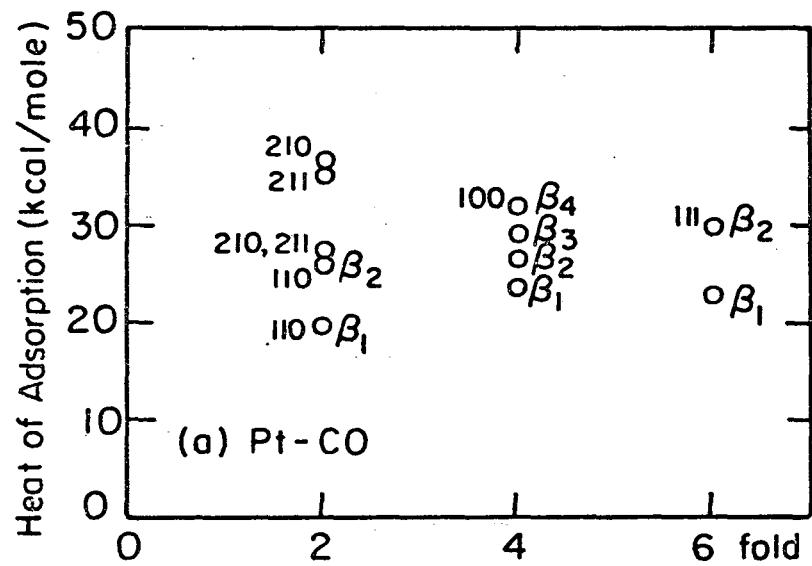


Fig. 15a

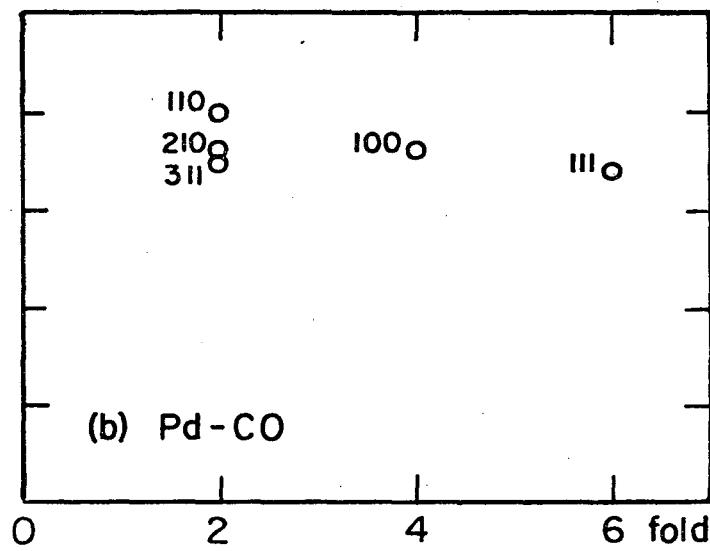
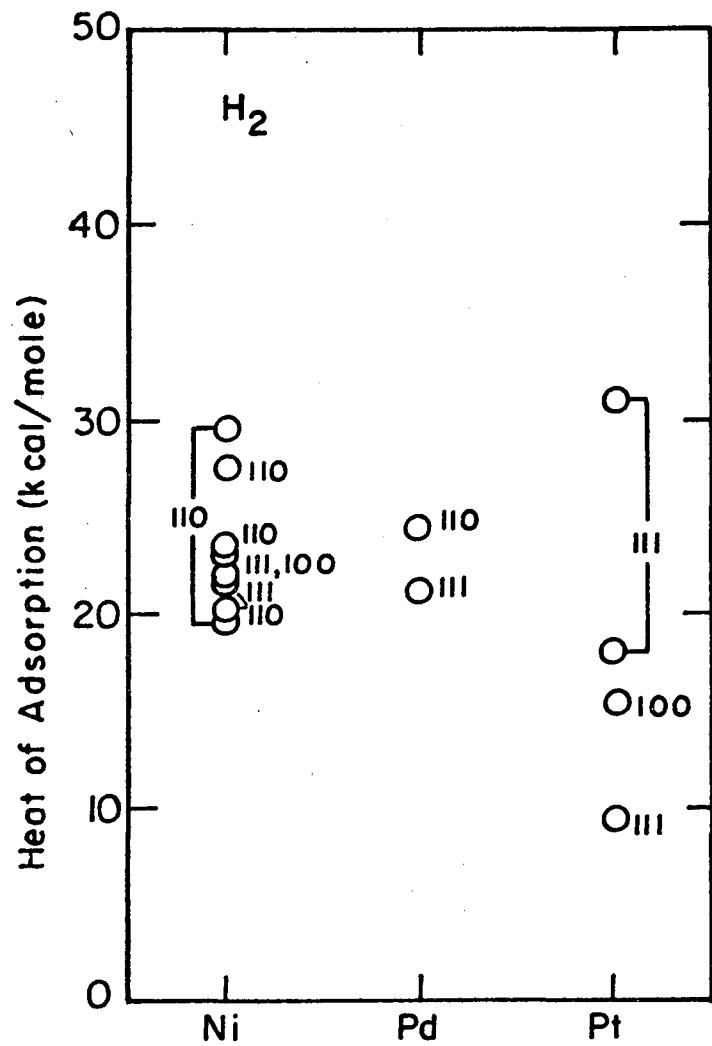


Fig. 15b

XBL 777-57II

0 0 0 0 4 8 0 5 9 5 6
-67-



XBL777-5709

Fig. 16

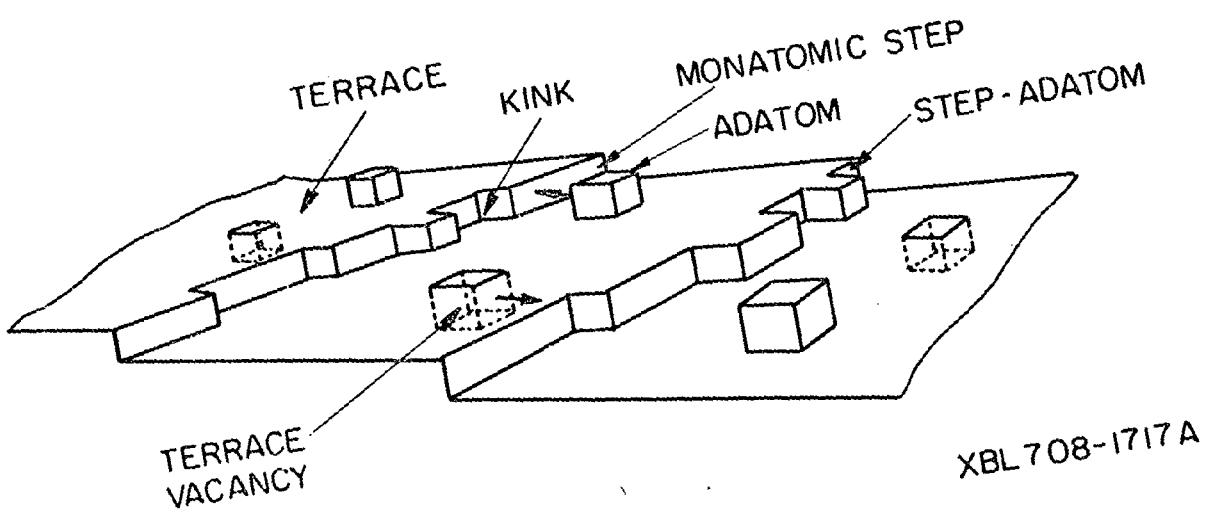


Fig. 17

0 0 0 0 4 8 0 0 9 5 7

This report was done with support from the Department of Energy.
Any conclusions or opinions expressed in this report represent solely
those of the author(s) and not necessarily those of The Regents of the
University of California, the Lawrence Berkeley Laboratory or the
Department of Energy.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720