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**The Conversion of Acetylene to Benzene  
Over Palladium Single Crystal Surfaces  
II. The Effect of Additives.**

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**Abstract**

The conversion of acetylene to benzene over palladium single crystal surfaces ((111), (100) & (110)) modified with submonolayer quantities of silicon, phosphorus, sulfur, chlorine and potassium has been studied under both ultra-high vacuum and atmospheric pressure conditions. At atmospheric pressures electron donating additives enhance the rate of benzene formation and electron accepting additives reduce the rate. Potassium and silicon reduce the amount of surface carbon that accumulates during the reaction and thereby increase the rate of benzene formation relative to the undoped surface. The general trends of the (111), (100) and (110) faces indicate that at low pressures potassium suppresses, silicon and phosphorus enhance, and sulfur and chlorine leave unchanged the benzene yield. Silicon on the (100) face showed the greatest enhancement in the benzene yield possibly due to surface compound formation.

## 1.0 INTRODUCTION

Additives are widely used in both low pressure stoichiometric reactions and high pressure catalytic reactions to alter the product distribution, to raise the yield or to increase catalyst lifetime. It is not well understood how the additives modify the catalyst surface for these reactions. Two major types of interactions are possible: 1. a geometric effect due to site blocking and 2. an electronic effect due to the donation or depletion of electron density in the near surface region.

The conversion of acetylene to benzene has been shown to occur both in ultra-high vacuum and at higher pressures on a variety of palladium surfaces with different morphologies (single crystals [1-9], films [1] and small metal particles supported on alumina [1]) as well as over many homogeneous catalysts [10-12]. A comparison of the low pressure and high pressure reaction on palladium single crystals is described in detail in the previous paper [1]. In this paper we study the effects of silicon, phosphorus, sulfur, chlorine and potassium on the chemisorptive and catalytic properties of palladium (111), (100) and (110) single crystal surfaces on the cyclotrimerization of acetylene. The differences in additive behavior in the low pressure and the high pressure (1 atm) reactions are compared. The effect of the additives is quantified by catalytic rates of benzene production from acetylene, temperature programmed desorption (TPD) of hydrogen, acetylene, ethylene, benzene, and carbon monoxide and by work function measurements.

## 2.0 EXPERIMENTAL

Experiments were carried out in two ultrahigh vacuum (UHV) chambers. Low pressure experiments were conducted in a standard UHV chamber with a base pressure of  $1 \times 10^{-10}$  Torr. The chamber was equipped with a four-grid retarding field analyzer and glancing incidence electron gun for Auger electron spectroscopy (AES) and for work function changes as the surface was modified by additives. Changes in the work function were measured by the change in the onset energy of the secondary electron cascade, and were reproducible to within  $\pm 10\%$ .

The high pressure experiments were performed in a UHV/ high- pressure apparatus designed

for combined UHV surface analysis and high-pressure reaction studies [13] using small surface area catalyst samples. This chamber was equipped with a four-grid electron optics for low energy electron diffraction (LEED), a double pass cylindrical mirror analyzer with coaxial electron gun for AES, Ar<sup>+</sup> sputtering gun for crystal cleaning, a quadrupole mass spectrometer and a retractable internal isolation cell that constitutes part of a microbatch reactor operating in the pressure range of 10<sup>-2</sup> – 20 atm. The experimental procedure for both the high pressure and the low pressure studies are described in detail in the previous paper [1].

For additive-doping studies, coverages were estimated using the relative Auger sensitivities of the most intense peaks [14], which is accurate only for low coverages. The relative additive coverage is given as  $\theta_A = (h_A S_A)/(h_A S_A + h_S S_S)$ , where  $h_A$  and  $h_S$  are the peak heights of the adsorbate and substrate and  $S_A$  and  $S_S$  are the Auger sensitivity factors for the adsorbate and substrate. Potassium was deposited under vacuum from a SAES getters mounted 2 cm from the sample. Silicon (Matheson grade SiH<sub>4</sub>), phosphorus (Matheson grade PH<sub>3</sub>), sulfur (Matheson grade H<sub>2</sub>S) and chlorine (Matheson H.P. grade Cl<sub>2</sub>) were deposited on the crystal surface at 300 K through a variable rate leak valve. Subsequently, the crystal surface was heated (700 K) to desorb H<sub>2</sub>, and the coverage was determined by AES. Additive coverages remained unchanged, as observed with AES during both UHV and high pressure experiments.

Product formation was followed by gas chromatography. Initial reaction rates were determined graphically from the slopes of product accumulation curves as a function of time over the first two to three hours of reaction time and were reproducible to within ±10%. Blank experiments performed on Pd covered with graphitic carbon (formed by heating the crystal in a hydrocarbon atmosphere at 750 K) showed only a low level of catalytic activity. For example, at 575 K the activity of the carbon-covered surface was less than 10% of the activity of clean palladium at the lowest reaction temperature (275 K) used in this study.

### 3.0 RESULTS

The cyclotrimerization of acetylene was observed on adsorbate-modified (111), (100) and (110) single crystals of Pd. These surfaces have been studied in ultrahigh vacuum using TPD and at

1 atm pressure using the high pressure/low pressure apparatus to obtain kinetic information on the reaction. Detailed information on the trimerization reaction in both pressure regions on clean Pd is reported in the previous paper [1].

### **3.1 Effect of adatoms (Si,P,S,Cl and K) on the low pressure stoichiometric reaction over palladium single crystals.**

Thermal desorption studies were carried out in UHV for three Pd surfaces ((111), (100) and (110)) to determine the effect of adatoms (Si,P,S,Cl and K) on the acetylene cyclotrimerization, the decomposition of acetylene to carbon and hydrogen, the self- hydrogenation to ethylene and the reversible molecular desorption of acetylene. All doses were 6 Langmuir ( $L=1 \times 10^{-6}$  Torr sec) and at 130 K unless stated otherwise.

#### **3.1.1 Pd(111)**

As reported previously [1] TPD of 6 L of acetylene from clean Pd(111) resulted in some reversible molecular desorption at low temperatures (190 K), self hydrogenation to form ethylene (300 K), decomposition to form hydrogen (430-830 K) and formation of benzene (250-490 K) (Fig. 1).

Adsorption of silicon ( $\theta=0.25$ ) on Pd(111) did not significantly perturb the benzene formation as shown by the thermal desorption results (Fig. 2). The only effect of silicon was to slightly decrease acetylene decomposition and enhance the high temperature desorption peak of benzene. Phosphorus, on the other hand, greatly suppressed the acetylene decomposition, increased the yield of ethylene and gave rise to a thermal desorption spectrum of benzene (from the cyclotrimerization reaction) with maxima at 200, 300, 400 and 470 K, while doubling the benzene yield (Fig. 2).

Sulfur adatoms also affected the thermal behavior of chemisorbed acetylene (Fig. 2). At low sulfur coverages ( $\theta < 0.2$ ), the decomposition to hydrogen and the ethylene yield decreased, while the benzene yield increased significantly. The low temperature benzene peak intensity almost doubled relative to the clean surface and a new peak appeared at 430 K. At higher sulfur coverages ( $\theta < 0.25$  ML), the formation of ethylene was fully suppressed and the decomposition



to  $H_2$  was very low. At these high sulfur coverages, the benzene desorption spectrum comprised a broad peak with a single maximum at 260 K equal in intensity to the clean surface.

Like phosphorus and sulfur, chlorine adatoms also enhanced benzene formation (Fig. 2). In contrast to sulfur, the benzene desorbed largely in the high temperature regions, with maxima at 415 and 490 K, although there was a smaller peak at 270 K. Chlorine also suppressed ethylene formation and acetylene decomposition.

The adatoms increased acetylene cyclotrimerization and decreased side reactions in order from silicon to phosphorus to sulfur on Pd(111). Chlorine was not as effective as sulfur, which almost fully suppressed all acetylene reactions except for cyclotrimerization. Thus Pd(111)-S is a selective catalyst for acetylene cyclotrimerization under UHV conditions. The main difference in the TPD spectra between the Pd(111)-S and Pd(111)-Cl surfaces was that the Pd(111)-S surface promoted primarily the low temperature cyclotrimerization reaction and the Pd(111)-Cl surface promoted the high temperature process.

TPD studies of adsorbed benzene on adatom-covered palladium surfaces yielded similar desorption spectra as benzene formed from acetylene. Figure 3 shows the effect of silicon ( $\theta = 0.25$ ) on Pd(111) on the desorption of benzene and benzene formed from acetylene. Silicon enhanced the high temperature TPD peak of benzene relative to the clean surface for both acetylene and benzene adsorption. Higher exposures of both acetylene and benzene led to an enhancement of the high temperature (470 K) benzene desorption peak.

### 3.1.2 Pd(110)

Acetylene chemisorbed on clean Pd(110) resulted in reversible molecular desorption, decomposition, self hydrogenation and cyclotrimerization. The yield of benzene from the clean Pd(110) crystal face was found to be approximately one-sixth that of the clean Pd(111) crystal face.

Silicon at low surface coverages ( $\theta < 0.25$ ) enhanced the benzene yield through the high temperature desorption peak (Fig. 4) and decreased acetylene decomposition. At  $\theta_{Si} = 0.37$  the yield of benzene increased by a factor of 3.5 (relative to the clean surface), while the ethylene and hydrogen yields were less than that observed for the clean Pd(110) surface.

Phosphorus on the (110) surface of palladium increased cyclotrimerization and self hydrogenation. Benzene desorption was found to increase at phosphorus coverages greater than  $\theta = 0.2$ . Again, as on Pd(111) and Pd(100), the gain in benzene yield was in the high temperature desorption peak (Fig. 4). At higher phosphorus coverages, two benzene TPD maxima were observed at 270 K and 440 K. The high temperature maximum was increased by as much as a factor of 4 ( $\theta_P = 0.42$ ) relative to the clean surface, while the ethylene yield remained at the level of the low coverage surface. The amount of hydrogen desorption decreased.

The benzene yield increased slightly, the ethylene yield decreased and the molecular desorption of acetylene increased with increasing amounts of sulfur on the surface. At higher sulfur coverages ( $\theta_S = 0.4$ ) no ethylene was detected, very little hydrogen desorbed, and the amount of benzene formed was approximately the same as on the clean Pd(110).

Addition of chlorine to Pd(110) decreased decomposition, hydrogenation and cyclotrimerization of acetylene. At a chlorine coverage of  $\theta = 0.30$ , a very weak ethylene desorption peak was observed at 290 K and a broad benzene desorption maximum was observed at 370 K (Fig. 4).

### 3.1.3 Pd(100)

A TPD experiment after acetylene adsorption on clean Pd(100) yielded reversible molecular desorption, decomposition, hydrogenation and cyclotrimerization (Fig. 5A-D). The yield of benzene from the clean Pd(100) crystal face was 1/20th that of the clean Pd(111) crystal face.

Potassium on the (100) face of palladium inhibited benzene formation (Fig. 5A). The yield of ethylene and hydrogen decreased by 95% (Fig. 5B,D), and the molecular desorption of acetylene was slightly reduced (20-25%) (Fig. 5C). At  $\theta = 0.25$  (or higher) coverages of potassium, no benzene formation was observed.

Silicon on Pd(100) substantially enhanced benzene and ethylene formation (Fig. 5A,B). The two benzene TPD peaks were similarly affected by silicon promotion on Pd(100) and Pd(111); that is, the high temperature peak increased and accounted for a six-fold increase in the yield

of benzene at a silicon coverage of  $\theta = 0.10$ . Higher coverages of silicon on Pd(100) ( $\theta = 0.38$ ) further increased the yield of benzene, up to 20 times that of the clean surface (Fig. 6). The ethylene yield was also enhanced by factor of 10. The decomposition reaction increased as well, although the hydrogen desorption remained constant.

Phosphorus adsorbed on Pd(100) influenced the chemistry of chemisorbed acetylene. The yield of benzene was enhanced, but not to the extent observed on silicon-covered Pd(100). At a coverage of 0.17 ML of phosphorus, two benzene maxima were observed, at 350 and 520 K. Low coverages ( $\theta < 0.2$ ) did not change the benzene or ethylene yields. At coverages of  $0.3 < \theta_P < 0.5$ , the amount of both benzene and ethylene increased by a factor of 3 to 5 (Fig. 5A,B). With increasing phosphorus coverages the benzene desorption maxima were also observed to shift to higher temperatures, primarily to the high temperature desorption peak at 480K.

Low sulfur coverages on Pd(100) ( $\theta_S < 0.25$ ) decreased the yield of ethylene (Fig. 5B) and only slightly increased the benzene yield (Fig. 5A). The desorption of hydrogen decreased markedly for all sulfur coverages, and the desorption spectra was very broad, ranging from 435-610 K (Fig. 5D). The major change observed at higher sulfur coverages was the decrease in ethylene yield. For example, at  $\theta_S = 0.25$  the ethylene yield was one half that of the clean surface (Fig. 5B).

Chlorine was found to enhance the yield of both ethylene and benzene (Fig. 5A,B). The effect was much smaller than that observed for either silicon or phosphorus. For coverages of  $\theta_{Cl} = 0.3$  the yield of benzene was 5 times higher than for the clean surface.

The additive coverage dependence of benzene formation was studied on the Pd(100) surface (Fig. 6). Sulfur and chlorine enhanced benzene formation up to coverages of  $\theta = 0.25$  and at higher coverages hindered benzene formation. Silicon and phosphorus increase benzene production to the highest coverages studied ( $\theta = 0.4$ ).

### 3.2 Effect of adatoms (K,Si,P,S and Cl) on the high pressure catalytic reaction on palladium single crystals.

High pressure catalytic studies were carried out over three palladium surfaces ((111),(100) and (110)) to determine the effect of adatoms on the acetylene cyclotrimerization. Reactions were carried out between 290 K and 620 K at an acetylene pressure of 200 Torr. Reaction rates were calculated by assuming that each palladium surface atom was one reaction site, and no correction was made when adatoms were deposited on the surface. This leads us to report conservative values for the reaction rates. All reactions produced benzene and very small amounts of C<sub>4</sub> hydrocarbons. Small amounts of ethylene (<5% of the benzene formed) were not detectable by gas chromatography due to the large acetylene reactant gas peak tail.

#### 3.2.1 Pd(111) and Pd(100)

The initial rate of benzene production on clean Pd(111) and Pd(100) at 573 K with 200 Torr of acetylene was found to be 0.05 molecules of benzene produced per palladium surface atom per second [1]. Potassium had the greatest positive effect on the rate of benzene production on Pd(111) (Fig. 7). With  $\theta_K = 0.25$  of potassium (200 Torr acetylene, 850 Torr Nitrogen, 570 K) the rate doubled to 0.10 molecules/site sec. When potassium was present on the surface, less graphitic carbon appeared in AES (due to the decomposition reaction) and the rate of poisoning was reduced relative to the clean surface. Silicon also accelerated the rate of benzene formation. For example, at a coverage of  $\theta_{Si} = 0.33$  the rate increased by 35%. Similarly, relative to the reaction over clean Pd(111), the amount of graphitic carbon deposition was reduced with silicon present on the surface. The amount of graphitic carbon on the surface after the reaction was determined by CO titration, as described in the previous paper [1].

Phosphorus depressed the reaction rate (Fig. 7). At  $\theta_P = 0.33$  the rate of benzene production was reduced by 37%. The graphitic carbon deposition rate and the poisoning rate were similar to that of clean Pd(111).

Sulfur and chlorine greatly depressed the reaction rate. For coverages greater than  $\theta = 0.20$ ,

no benzene formed. Reactions on chlorinated surfaces were carried out at room temperature due to the low desorption temperature of chlorine from palladium surfaces under reaction conditions. The facile desorption of chlorine under reaction conditions (300K, 250 Torr Acetylene, 850 Torr Nitrogen) is in sharp contrast to the reported desorption temperature in UHV of 950 K [15]. The rate of benzene formation on chlorine covered surfaces was very low, even for coverages as low as  $\theta = 0.1$ . For coverages over  $\theta = 0.2$  no benzene was observed.

The activation energy and pressure dependence for benzene formation on additive covered surfaces did not change from the values obtained on the clean surface (Activation Energy = 2.1 kcal mol<sup>-1</sup>, Rate =  $k P_{C_2H_2}^{+1}$ ) [1].

### 3.2.2 Pd(110)

The rate of benzene formation on clean Pd(110) was found to be 1/4 that of Pd(111) under the same reaction conditions [1]. Additives had less effect on the (110) surface than on the (111) and (100) surfaces. In contrast with potassium doping of the (111) and (100) surfaces, adsorption of potassium on the (110) surface decreased the rate of benzene formation (Fig. 7). Silicon and phosphorus both enhanced the rate of benzene formation to the same extent. As on Pd(111) and Pd(100), sulfur and chlorine depressed the reaction rate on the (110) surface.

## 4.0 DISCUSSION

The cyclotrimerization reaction of acetylene on clean Pd catalysts proceeds readily in pressures ranging from  $1 \times 10^{-12}$  - 1 atm and on a variety of surfaces (single crystals, films and alumina-supported) [1]. The reaction is structure sensitive at both low and high pressure. In UHV the stoichiometric reaction over the (111) face is the most active. The (110) face is one-sixth as active, and the (100) surface is one-twentieth as active as the (111) face. At high pressure the (111) and (100) surfaces show similar catalytic rates and the (110) face is one-fourth as active. In addition to the cyclotrimerization reaction, hydrogenation, reversible molecular desorption and decomposition reactions are detected at low pressure and decomposition / polymerization is detected at high pressure. At high pressure the reaction has an apparent

activation energy of  $2.1 \text{ kcal mol}^{-1}$  and is first order in acetylene pressure ( $\text{Rate} = k P_{\text{C}_2\text{H}_2}^{+1}$ ).

This study investigates the effect of additives (K, Si, P, S and Cl) on the cyclotrimerization of acetylene over palladium single crystals ((111), (110) and (100)) at both low and atmospheric pressures. The difference in benzene yield, at low pressures (relative to the differences in rate of benzene production at high pressures) over the different modified surfaces was quite dramatic. Potassium was found to virtually eliminate all benzene formation at low pressures, whereas at high pressures, in general, it was found to be the best promoter for the catalytic formation of benzene. Sulfur and chlorine, on the other hand, slightly enhanced the low pressure formation of benzene, while at higher pressures even very low coverages ( $\theta < 0.1$ ) of sulfur or chlorine poisoned the reaction, and above  $\theta = 0.25$  no benzene formation was observed. The effects of the different additives will be discussed in terms of steric (site blocking) and electronic (electron donating or withdrawing) interactions with the surface. The high pressure catalytic and the low pressure stoichiometric results will also be compared.

To observe how the surface electronegativity changes with the addition of different adatoms to the surface, we performed work function measurements on Pd(100) (Fig. 8). The change in work function varies linearly with the coverage of each additive. The decrease in work function is greatest for potassium, indicating that it donates the most electron density to the surface per unit coverage, followed by silicon and then phosphorus. Conversely, sulfur increases the work function, implying that it withdraws electron density from the surface. These trends correspond to previous work function trends reported for the Cl/Pd and K/Fe systems [15,25]. The work function changes observed correlate to the differences in Pauling electronegativities between the additives and palladium. Potassium (0.82) and silicon (1.9), which are more electropositive than Pd (2.2) donate electron density to the surface and decrease the work function. Sulfur (2.6) which is more electronegative withdraws electron density and increases the work function. Phosphorus (2.19), is essentially electroneutral with palladium, but work function measurements show that it decreases the work function.

Both acetylene and benzene are known to donate electrons to metal surfaces [16-18]. Acetylene has a low lying antibonding orbital which is partially filled in the presence of electron donors

on the metal surface, such as potassium, which destabilize the carbon-carbon bond [17]. Benzene's antibonding orbitals have lower binding energies and are not filled even in the presence of potassium as evidenced by the TPD and electron energy loss spectroscopy of this group [19,20].

Studies have found potassium to be uniformly dispersed on metal surfaces [21,22] (except at multilayer coverages), whereas sulfur and chlorine form ordered islands at low coverages [23]. Phosphorus and silicon form ordered LEED structures over some Pd surfaces [24]. For example on Pd(111), phosphorus formed a  $(\sqrt{7} \times \sqrt{7})R17^\circ$  pattern.

#### 4.1 Low Pressure Studies

The UHV results are summarized in Figure 9, which shows the effect of  $\theta = 0.25$  of additive on the benzene yield. The most pronounced effect was that of silicon on the Pd(100) surface, where, at a coverage of  $\theta_{Si} = 0.38$ , the yield of benzene increased twenty-fold. Phosphorus on the (100) surface increased the benzene yield approximately twelve-fold. The enhanced amount of benzene over these two surfaces may be attributed to the formation of surface compounds. Changes in the work function after annealing (770 K) for silicon on the Pd(100) surface supports this claim (Fig. 10). For a silicon coverage of  $\theta = 0.27$ , the work function increases approximately .75 eV, approaching the value of the clean palladium surface. This increase corresponds to silicon dissolution in the surface region, as shown by the slight change of the AES silicon signal (no silicon desorption was observed). This work function change has been shown to indicate surface compound formation [25-32]. PdSi is known to be a stable compound [33]. These changes in the work function were not observed for any of the other additives on the Pd(100) surface.

Potassium is the least likely of the additives studied to form islands on the metal surfaces and only at coverages approaching saturation do LEED patterns form [23]. Less initial reaction sites would be available for a potassium doped surface than would be for a silicon, phosphorus, sulfur or chlorine modified surface which form islands at low coverages. The negligible conversion of acetylene to benzene is possibly due to potassium blocking sites. With dispersed

potassium on the surface, three acetylene molecules would be less likely to be close enough together on the surface to form benzene.

Sulfur suppressed the decomposition reaction. Relative to the three clean surfaces, only 5-10% as much H<sub>2</sub> and ethylene were observed in the TPD experiments. Anderson and coworkers [16,17] predicted that electron withdrawing additives would block most acetylene adsorption and weaken the acetylene - metal bond. The weakened acetylene-palladium surface bond accounts for the large decrease in the amount of decomposition. Benzene formation remained approximately unchanged and molecular desorption was slightly enhanced.

Chlorine also reduced the amount of acetylene decomposition, but not to the same extent as sulfur. Molecular desorption of acetylene was enhanced. Benzene formation was enhanced slightly on Pd(100) while it declined slightly on Pd(111) and Pd(110). Chlorine should act very much like sulfur, because both additives withdraw electron density from the surface and form ordered structures at low coverages indicating island formation. It is interesting that for similar coverages of sulfur and chlorine that 2-10 times more hydrogen evolves from the chlorinated surface.

In general, the trend from K → Si → P → S → Cl seems to indicate that increasingly electron withdrawing additives lead to decreasing decomposition and increased benzene yields relative to the clean surface. The most electron withdrawing additive, chlorine, breaks this trend. The site blocking contribution to the surface reaction appears to be greatest for potassium and decreases as the additive becomes more electronegative.

#### 4.2 High Pressure Studies

The effect of additives (K, Si, P, S and Cl) at atmospheric pressures on the reaction of acetylene over single crystals of palladium has been investigated. The additives had the same effect on the Pd(111) and Pd(100) surfaces. The electron donating additives enhanced the rate of benzene formation (Fig. 7). Potassium and silicon, which donated the most electron density to the surface as determined by the change in work function, increased the reaction rate by a factor of 2 and 1.3 respectively, at a coverage of  $\theta = 0.3$ . Electron withdrawing additives



(S, Cl) decreased the rate of benzene formation and also increased the amount of carbon present on the surface after the reaction. The activation energy and pressure dependence for the formation of benzene did not change from the clean surface for all the modified surfaces studied.

The difference in the rate of benzene formation for the different modified surfaces is related to the amount of open Pd surface area. During the reaction, carbon deposited on the surface blocks reaction sites. This surface carbon could be in the form of graphite or a polymer with CH<sub>o</sub>C<sub>2</sub>H stoichiometry [9]. Electron withdrawing additives enhance the polymerization process, by acidifying the metal surface [34]. The increased surface carbon coverage decreases the rate of benzene formation. Figure 11 shows the amount of carbon present on the (100) surface after three hours of a high pressure reaction at room temperature, as detected by AES and CO titrations after flashing the modified surface to 520 K in UHV. Electron donating additives keep the surface cleaner by slowing the surface polymerization reaction. At high pressures the additives shift the product distribution of the acetylene reaction between benzene and surface polyacetylene or decomposition.

Phosphorus does not fit the trend of electron donors acting to enhance the rate of benzene formation. It appears to have slightly more carbon at equilibrium than the clean Pd(100) surface. The donating power of phosphorus is insufficient to stop either polymerization or decomposition.

The clean Pd(110) surface has only approximately 2% clean surface at steady state reaction conditions, which is used to explain the lower rate of benzene production relative to the other surfaces. The (110) surface of fcc metals can be thought of as a monotonically stepped surface. This high density of steps is expected to increase decomposition of acetylene, and lead to high surface carbon coverage.

The additives on Pd(110) had less effect on the rate of benzene formation than on the (111) and (100) surfaces. Surprisingly, potassium inhibited benzene formation whereas phosphorus enhanced the rate as much as silicon. The interaction of potassium on this surface is not well

understood.

## **5.0 CONCLUSIONS**

Our results for additive effects on the conversion of acetylene to benzene over palladium single crystals are quite different at high and low pressures. The high pressure catalytic results appear to depend on the amount of bare palladium exposed. At high pressures the surface is saturated with acetylene and the formation of benzene competes with the decomposition and polymerization reactions which poison the catalytic sites. Additives which keep the surface cleaner, such as potassium and silicon, enhance the rate of benzene formation. Sulfur and chlorine appear to enhance the polymerization or decomposition reactions which poison the catalytically active sites. The low pressure stoichiometric reaction that yields benzene from acetylene is inhibited by site blocking for electron donating additives, and enhanced due to electronic interactions for electron accepting additives.

From these results it is evident that the effect of the additives on the acetylene cyclotrimerization vary considerably between low pressure and atmospheric pressure. They exhibit both site blocking and electronic interactions that markedly change the benzene yield.

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## FIGURE CAPTIONS

**Figure 1.** The TPD spectra of acetylene dosed on clean Pd(111) (6L of acetylene, 130K) is displayed. The four desorption products are benzene from cyclotrimerization, ethylene from hydrogenation, acetylene from reversible molecular desorption and hydrogen from decomposition.

**Figure 2.** The benzene TPD from 6L acetylene dosed on additive covered covered Pd(111) at 130 K is displayed. The high temperature peak shifts to higher temperatures: from 470 K on the silicon dosed surface to 490 K on the chlorine covered surface. The phosphorus covered surface leads to a thermal desorption trace for benzene with four maxima. All spectra magnified by a factor of 2.

**Figure 3.** Benzene TPD spectra are compared after dosing silicon doped Pd(111) with 4L of acetylene or benzene at 130 K. Benzene formed from acetylene yields a broader high temperature peak. Higher acetylene exposures enhance the high temperature peak, whereas larger benzene exposures increase the low temperature peak.

**Figure 4.** The benzene TPD spectra from additive covered Pd(110) after a 6L exposure of acetylene at 130 K are displayed. Silicon and phosphorus increase the high temperature peak. Sulfur enhances the low temperature benzene desorption maxima slightly and chlorine reduces the overall yield and broadens the two maxima into one peak.

**Figure 5.** Figures A-D present the desorption traces for benzene, ethylene, acetylene and hydrogen from additive covered Pd(100) dosed with 6 L of acetylene at 130 K. Note the scaling factors. The benzene desorption changes both in the desorption temperature and desorption yield. Potassium suppresses desorption of all products except for acetylene. Silicon covered Pd(100) produces 15 times more benzene than the clean surface.

**Figure 6.** The benzene TPD peak area on Pd(100) is shown as a function of additive coverage after dosing with 6L of acetylene at 130 K. Electron-withdrawing additives, sulfur and chlorine, and electron-neutral phosphorus alter benzene formation to the same extent: initially increasing benzene formation and then for coverages greater than  $\theta = 0.22$  decreasing benzene

formation. Silicon enhances benzene formation to  $\theta = 0.38$  ( highest coverage studied) at which point 20 times more benzene forms than on the clean surface.

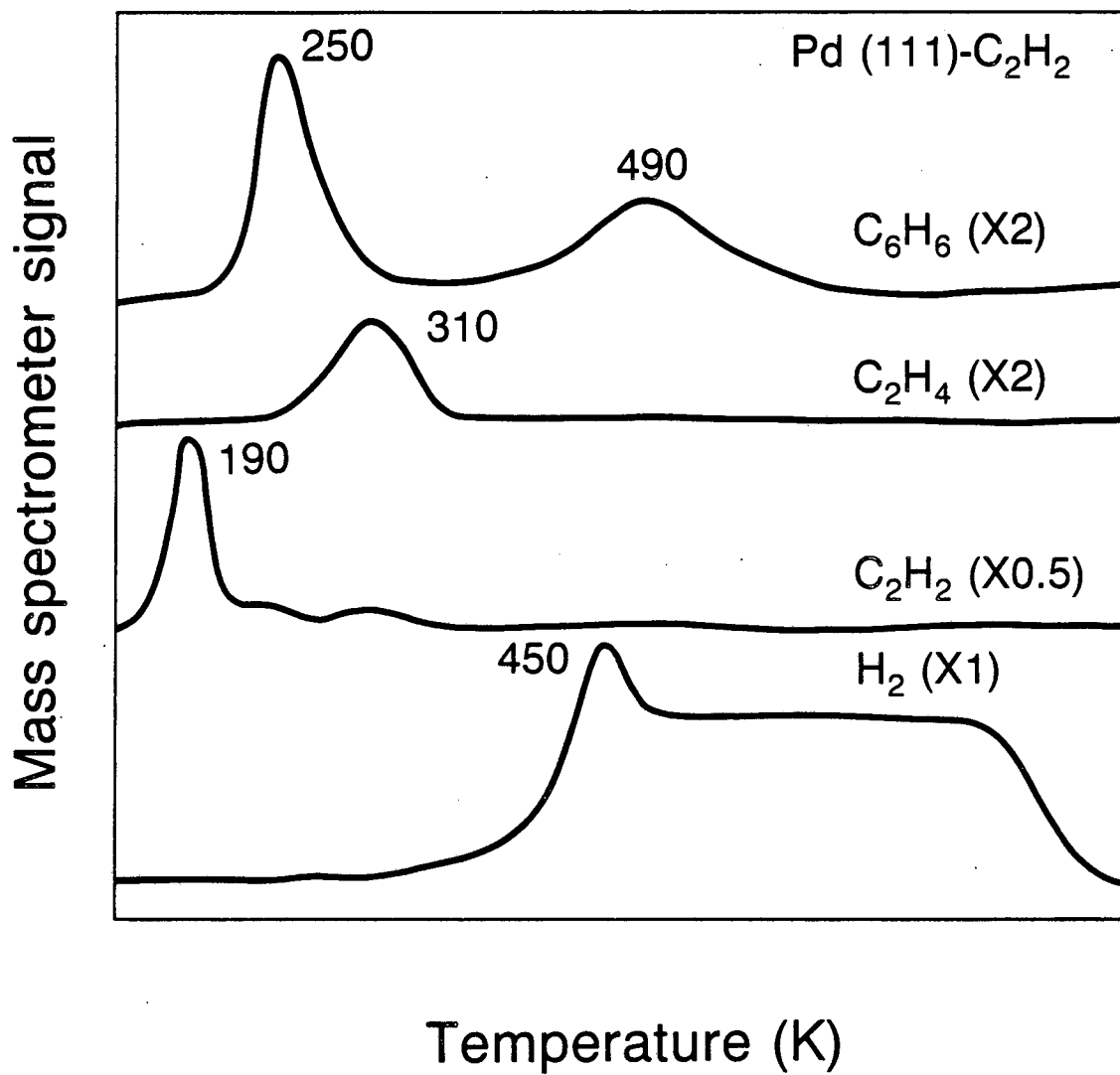
**Figure 7.** The effect of additives on the catalytic rate of benzene formation at atmospheric pressures on the Pd(111), Pd(100) and Pd(110) surfaces is shown. The additives have the same effect on Pd(111) and Pd(100). Potassium and silicon enhance the rate and phosphorus, sulfur and chlorine decrease the rate of benzene formation. On Pd(110) surface, which has a lower rate on the clean surface, silicon and phosphorus enhance the rate of benzene formation whereas sulfur, chlorine and potassium decrease the rate.

**Figure 8.** The change in work function is plotted versus the additive coverage on the Pd(100) surface. Sulfur withdraws electron density from the surface whereas potassium, silicon and phosphorus donate electron density to the surface.

**Figure 9.** This figure compares the effect of  $\theta = 0.25$  of additives on the benzene yield at low pressures on Pd(111), Pd(110) and Pd(100). Benzene TPD spectra were recorded after a 6L dose of acetylene at 130 K. Phosphorus on Pd(111) and silicon on Pd(100) increase benzene formation the most.

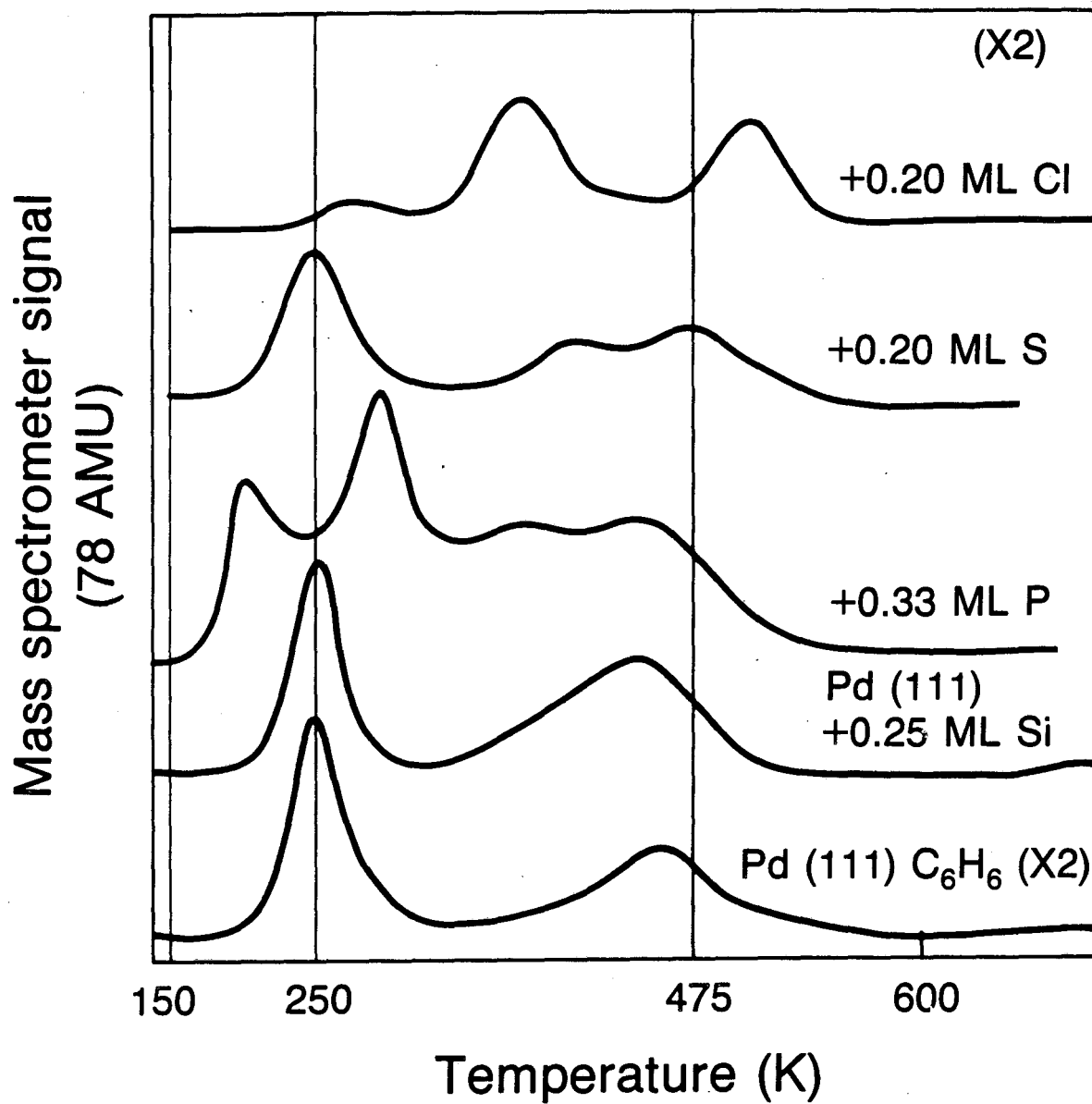
**Figure 10.** The change in work function is plotted as a function of silicon coverage on Pd(100). After annealing the crystal at 770 K for four minutes the work function shifts 0.75-1.25 eV, while the silicon coverage, as detected by AES, remains almost constant.

**Figure 11.** The effect of additives on the final carbon coverage for Pd(100) is shown here. Electron-donating additives (potassium, silicon) limit carbon buildup on the surface relative to the undoped surface. Electron-withdrawing additives have higher carbon levels and faster rates of poisoning relative to the undoped surface. Carbon coverage measured after three hours of reaction time.



XBL 856-11208

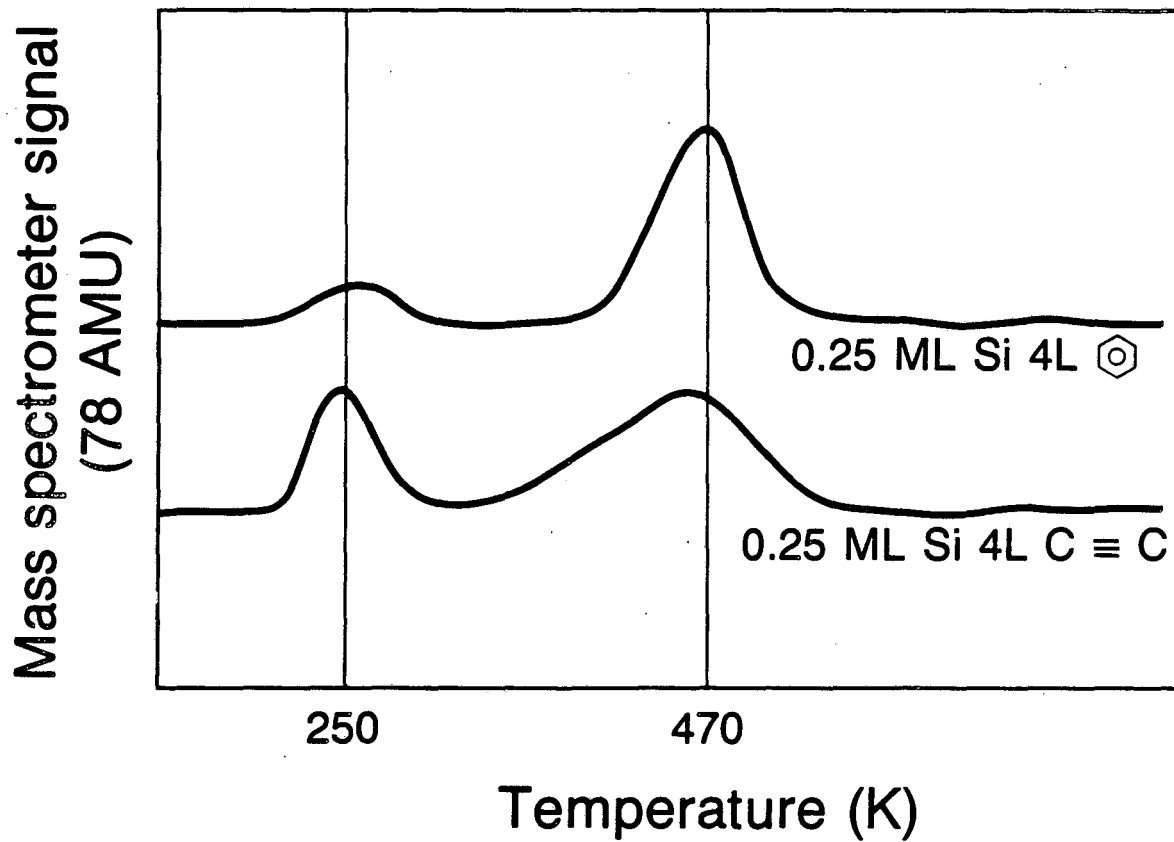
FIGURE 1



XBL 856-11206

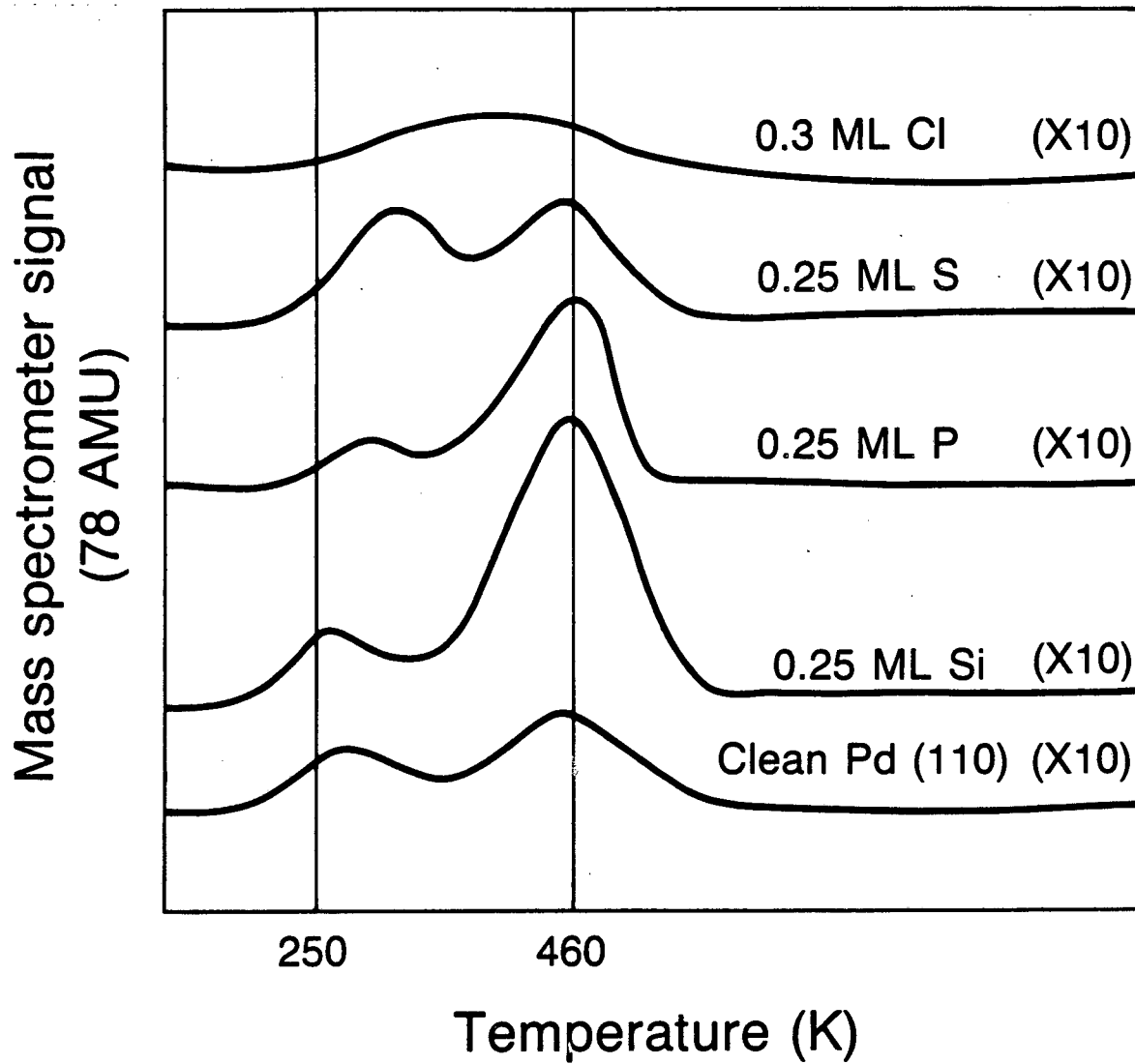
FIGURE 2





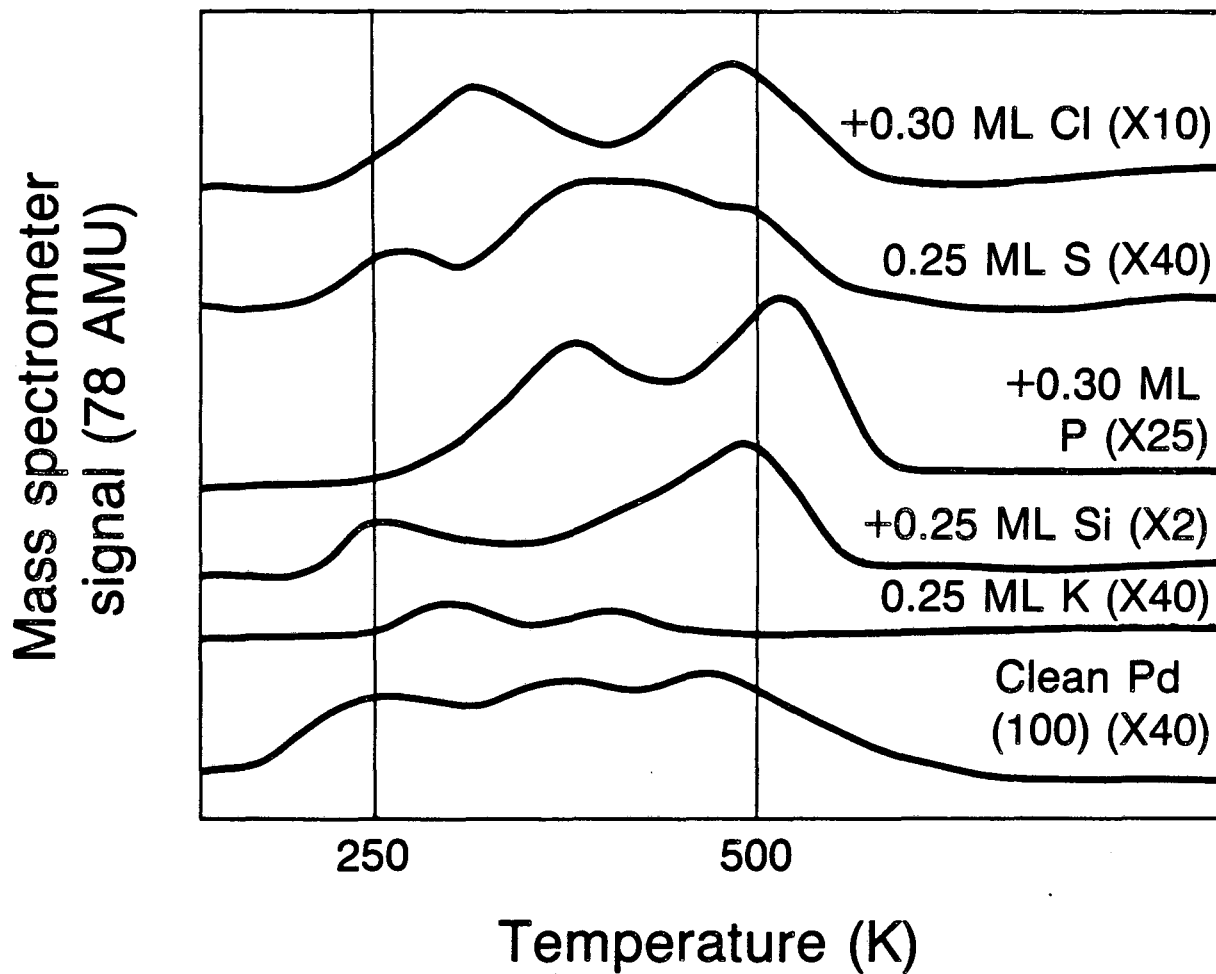
XBL 856-11205

FIGURE 3



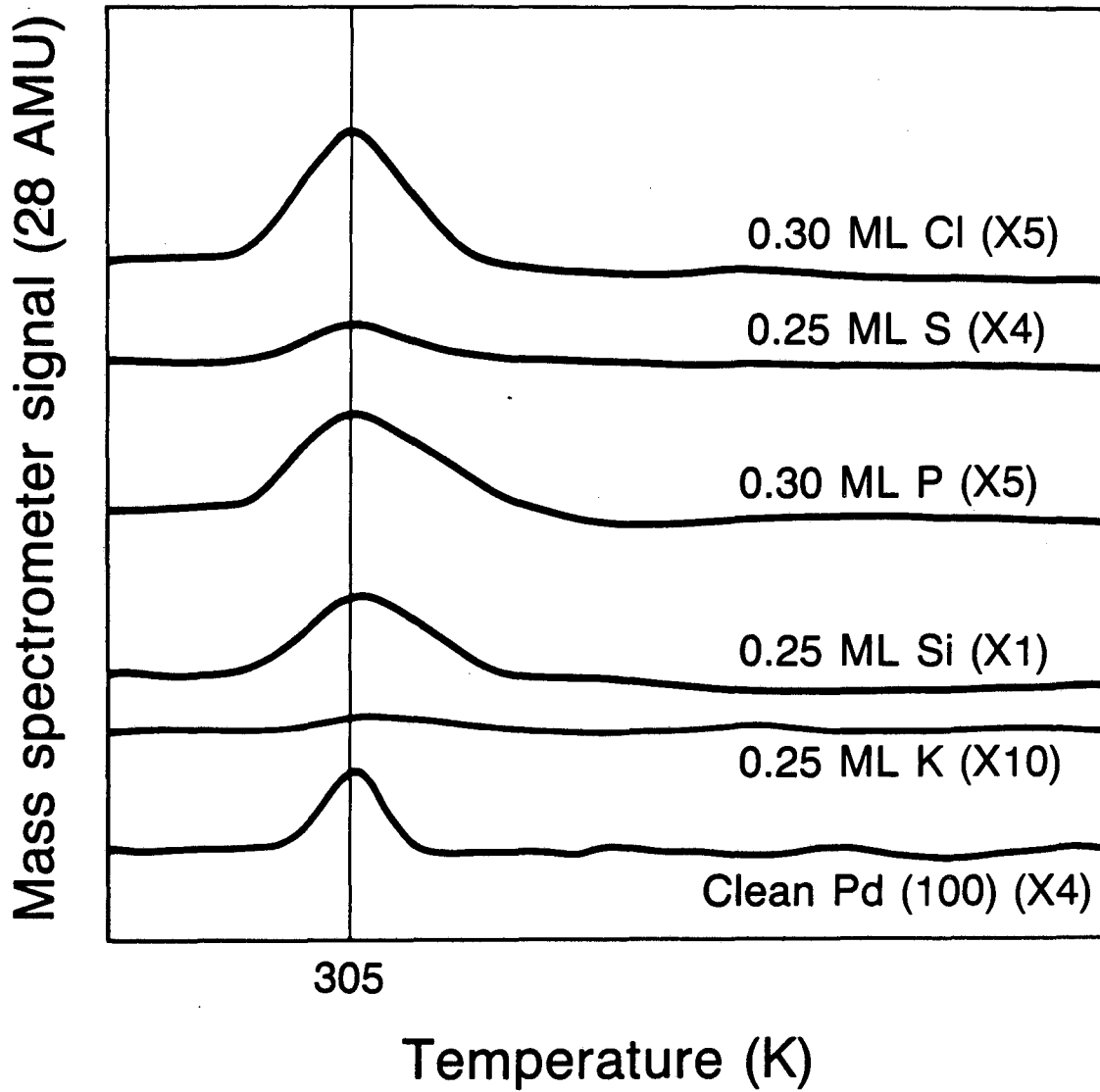
XBL 856-11207

FIGURE 4



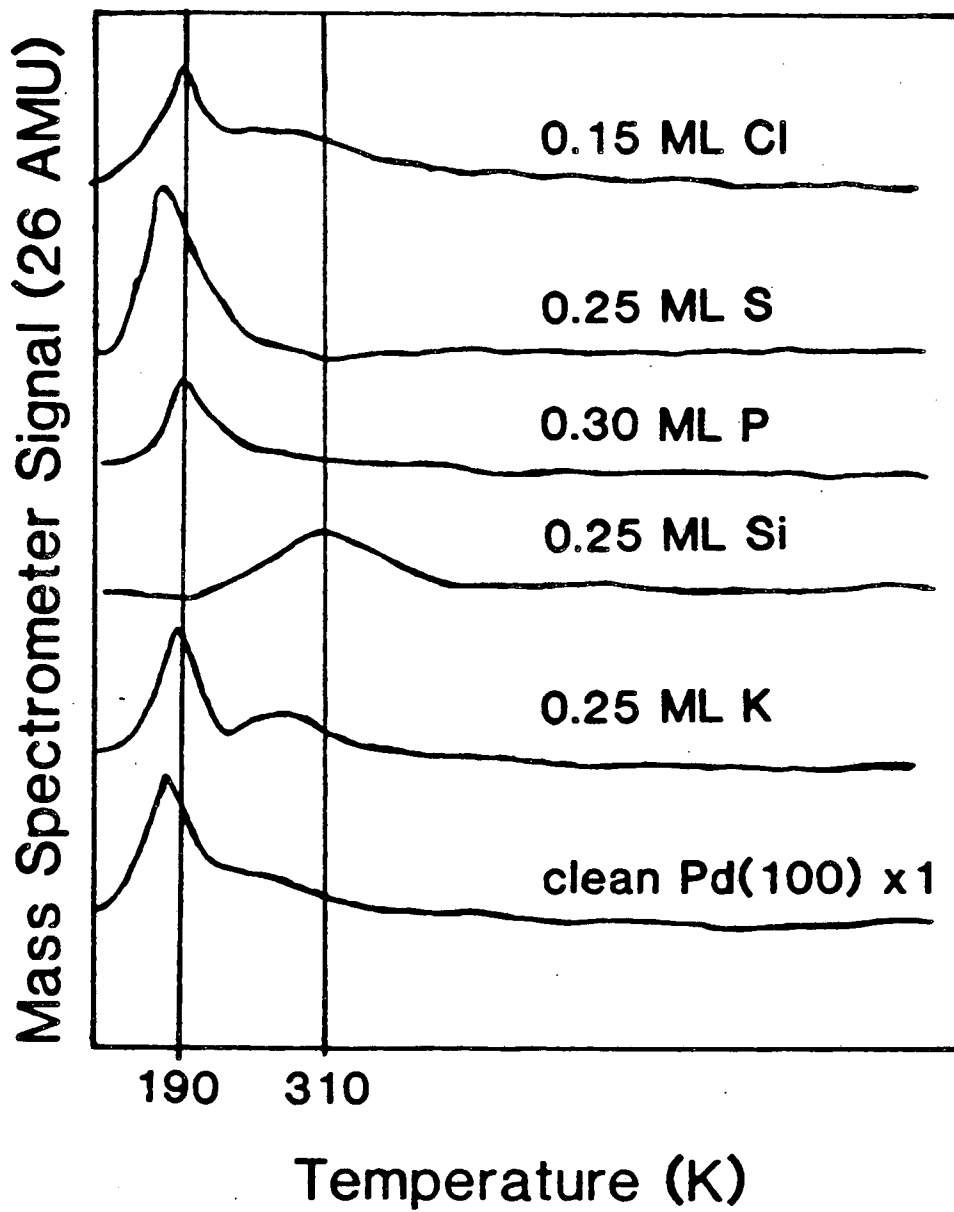
XBL 856-11204

FIGURE 5A



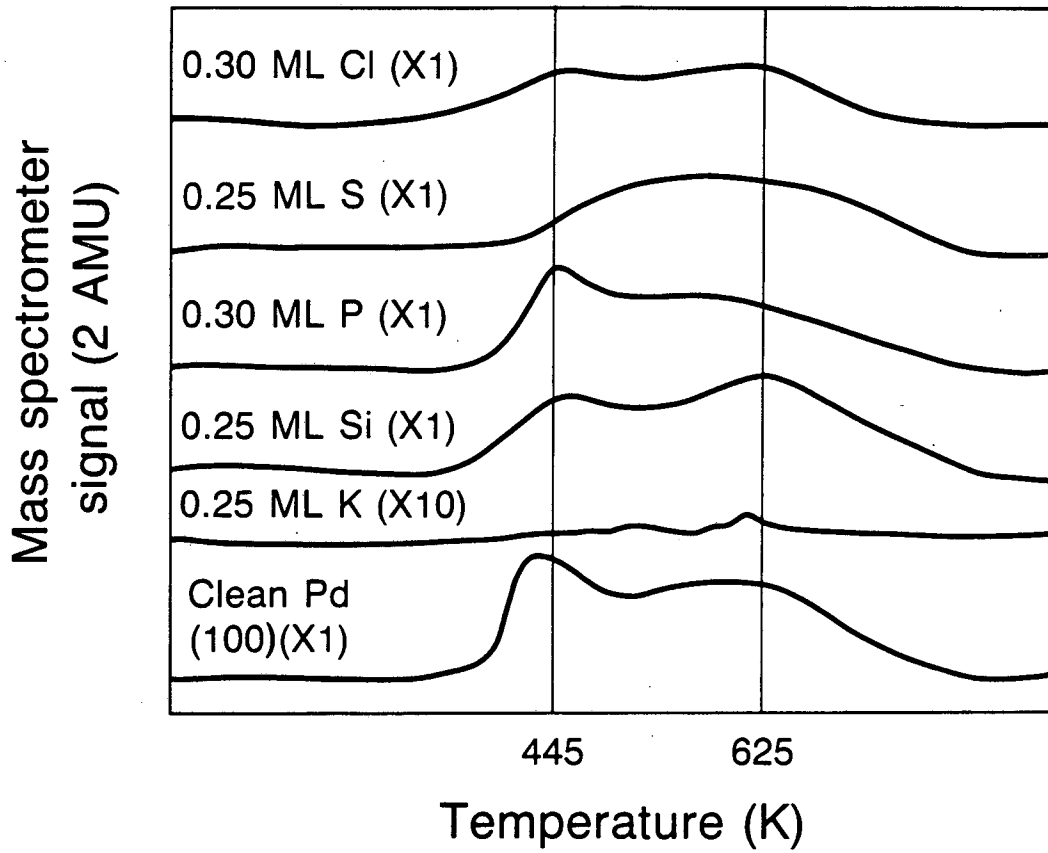
XBL 856-11209

FIGURE 5B



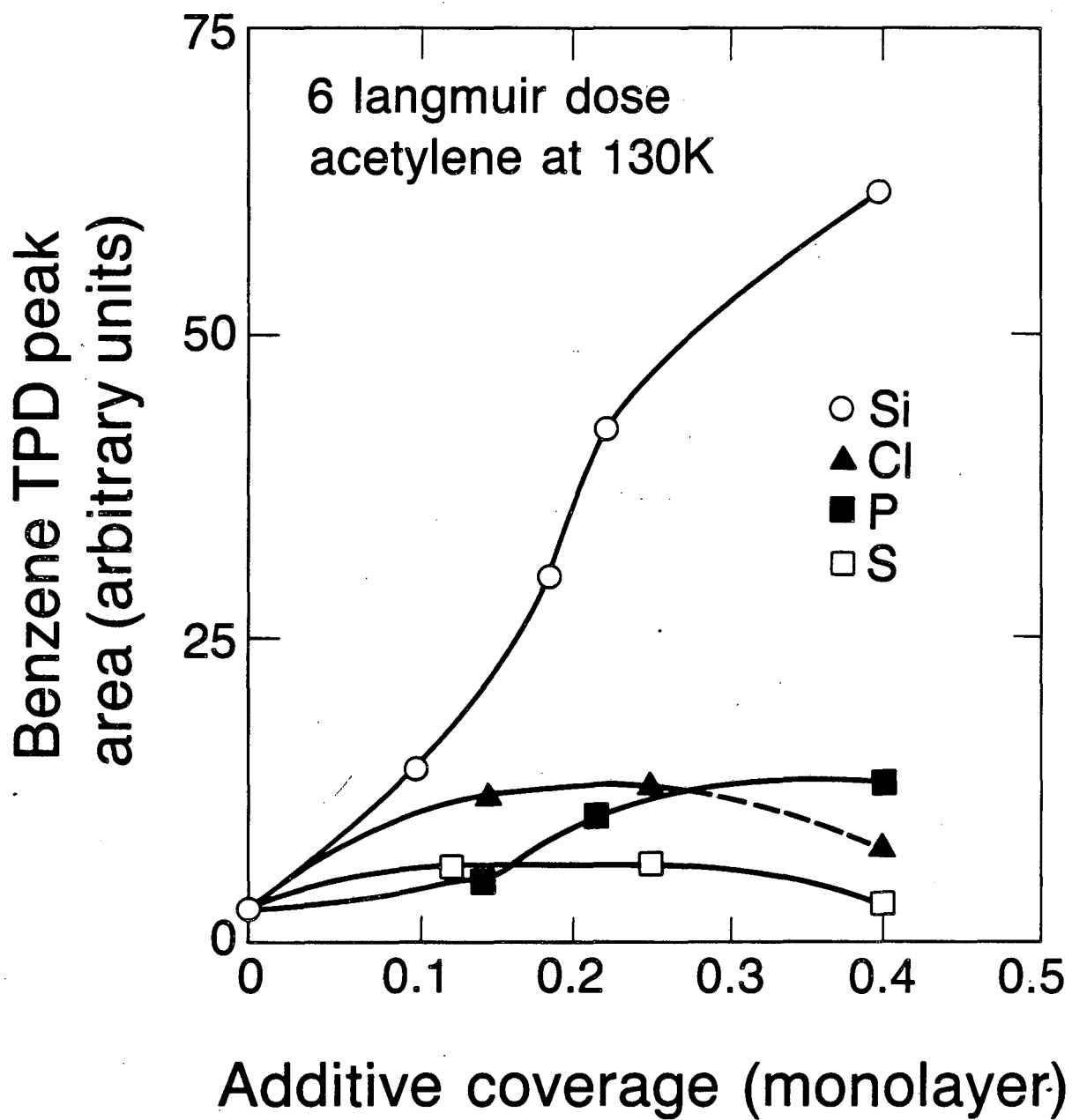
XBL 858-3211

FIGURE 5C



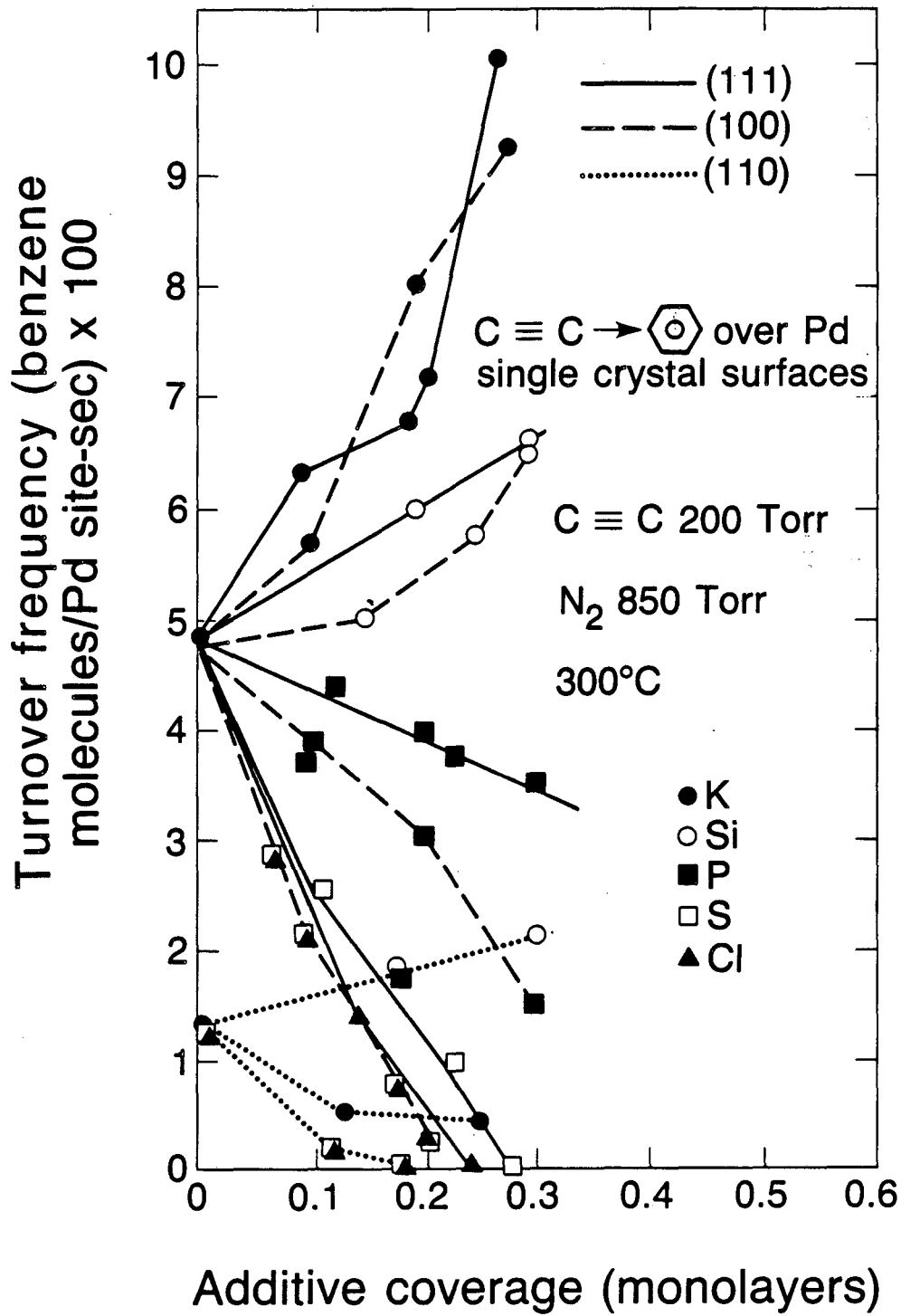
XBL 856-11210

FIGURE 5D



XBL 856-11215

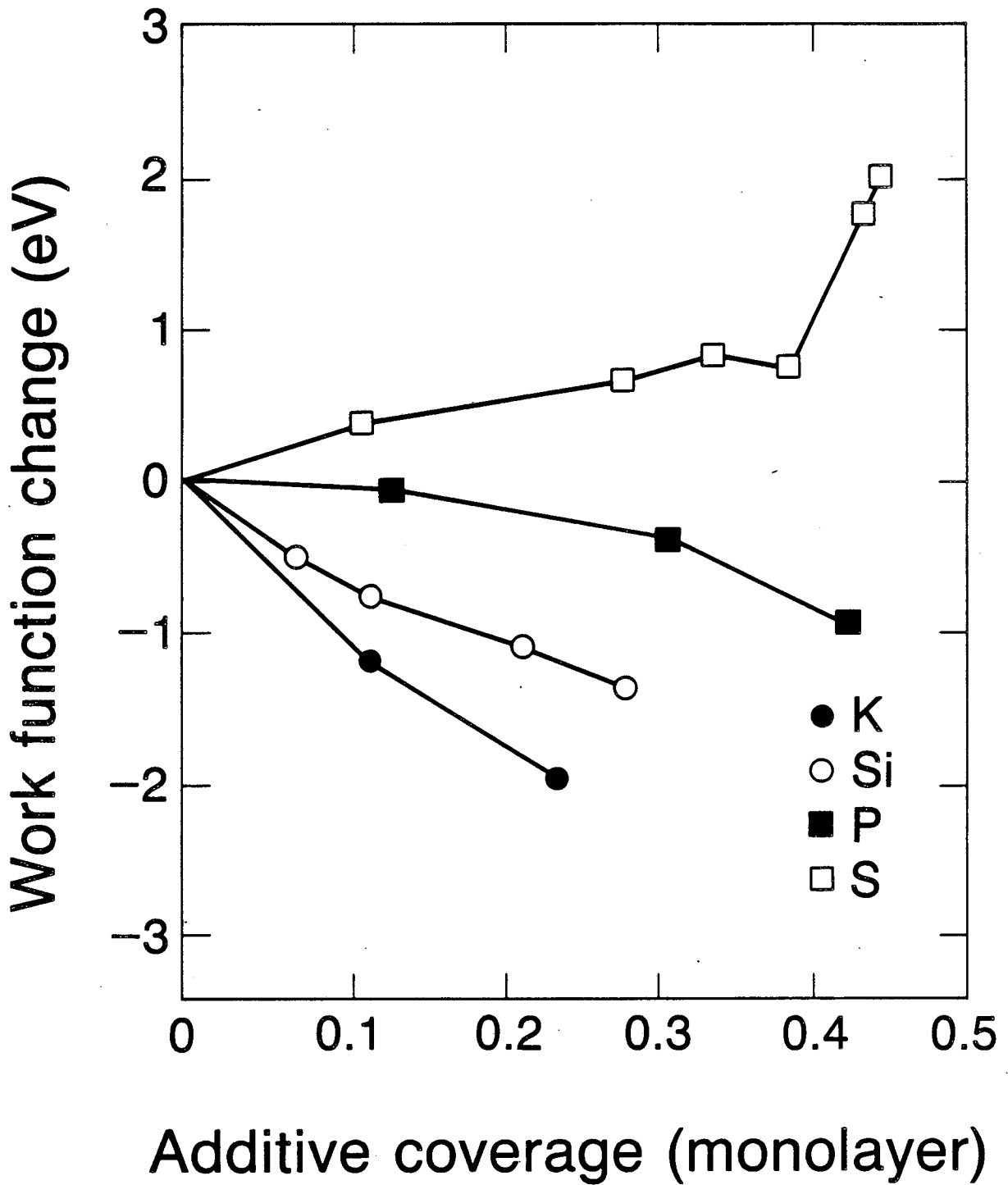
FIGURE 6



XBL 856-11214

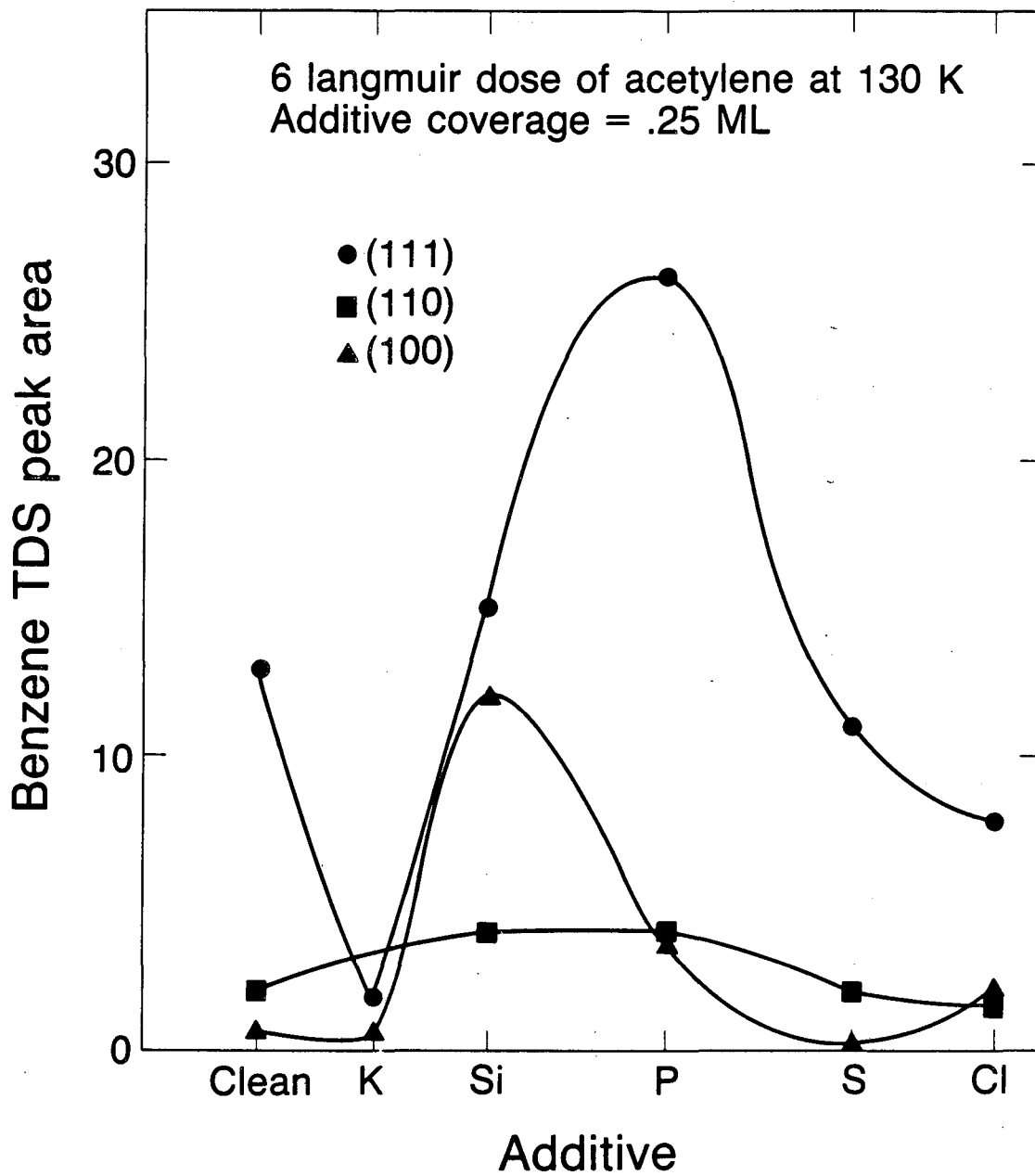
FIGURE 7





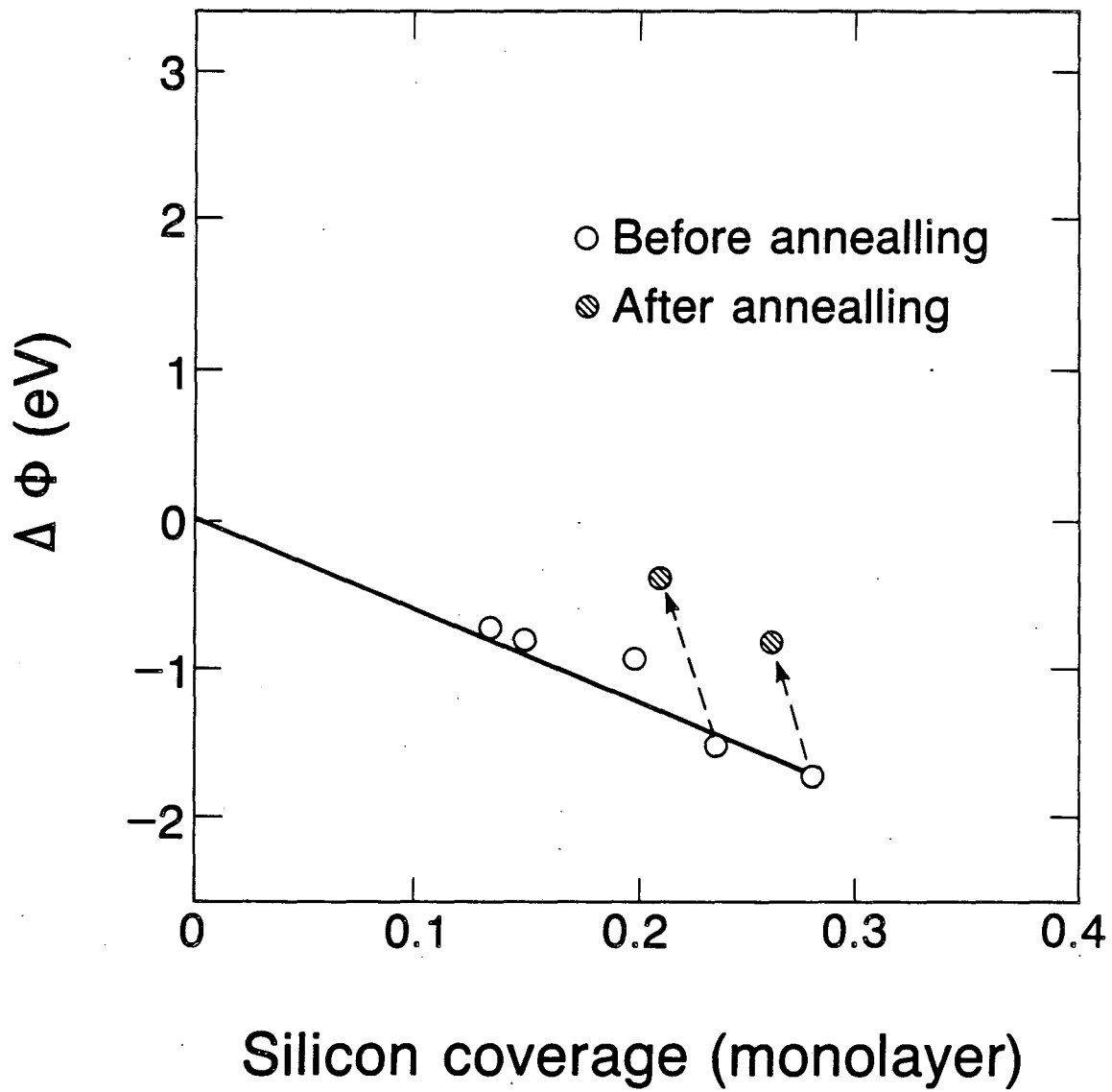
XBL 856-11197

FIGURE 8



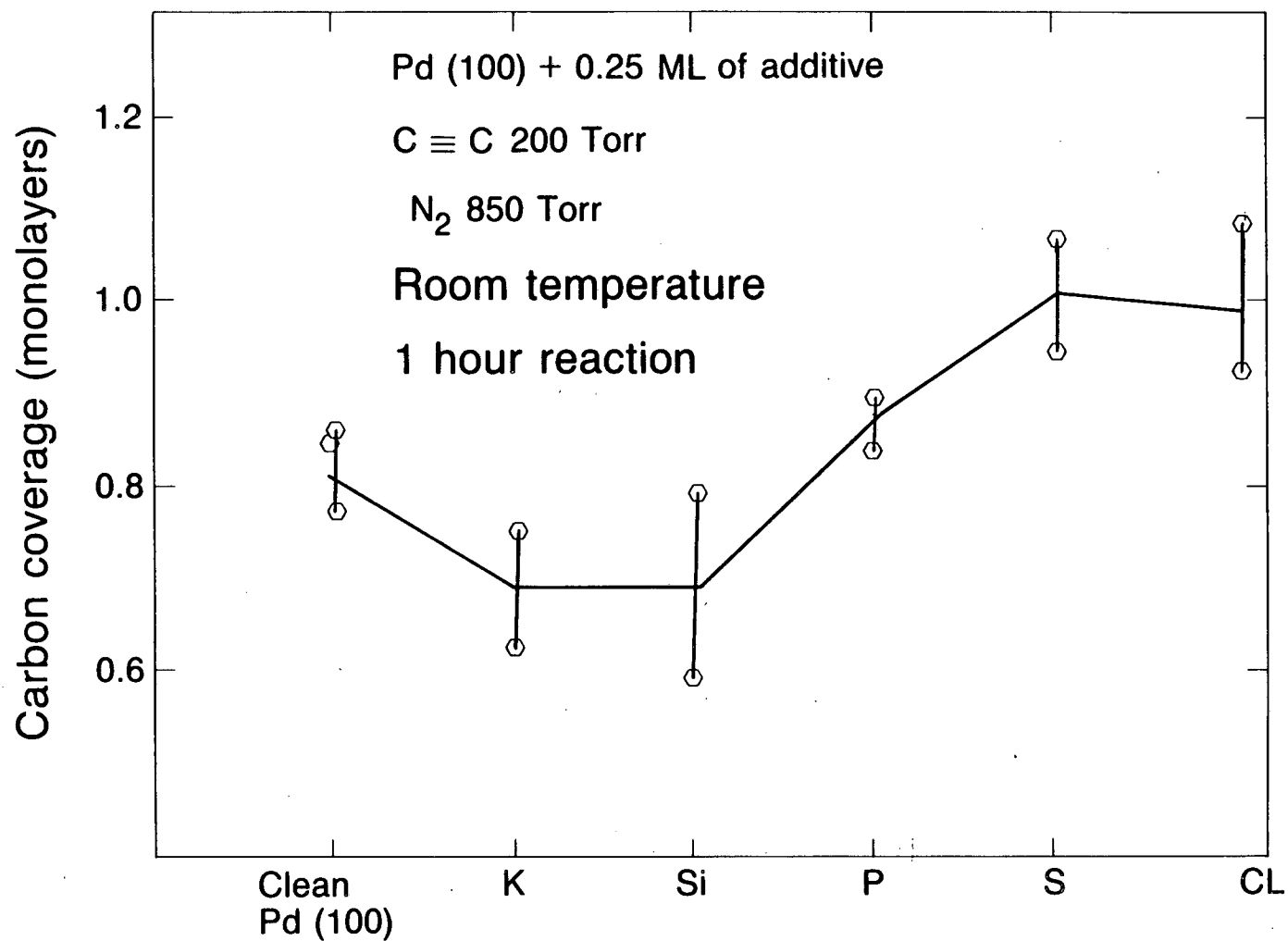
XBL 856-11211

FIGURE 9



XBL 856-11198

FIGURE 10



XBL 856-11200

FIGURE 11

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