Enhancement of Pb(II) ions adsorption onto magnesium loaded activated carbon in aqueous solution

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Magnesium loaded activated carbon was prepared to increase the adsorption capacity of lead (II) ions from aqueous solution. In case of sufficient amounts of surface acidic functional groups existing on the carbon, no significant improvement of heavy metal removal was observed even if the magnesium was loaded on it, but removing surface oxygen compounds by out-gassing in helium flow at 1173 K before magnesium loading, considerable enhancement of the heavy metal adsorption affinity onto the activated carbon could be observed. The amount of magnesium impregnation in the aqueous solution was also increased using the out-gassed carbon in the preparation. Any detrimental effect was not observed for aromatics adsorption by the introduction of magnesium. All adsorption equilibrium results at 293 K obeyed Langmuir isotherms. Heavy metal ions adsorption onto the magnesium loaded activated carbons progressed via ion exchange mechanism. Based on the Boehm titration surface analysis, the strong heavy metal adsorption sites might be generated forming the magnesium bound to carbon surface via oxygen bridge by means of calcining the magnesium nitrate impregnated out-gassing carbon in air at 653 K.

KEYWORDS : Activated carbon, Calcination, Coating, Adsorption, Surface properties

1. Introduction

Heavy metals are threat for human beings as well as ecosystems. A much amounts of heavy metals have been widely exhausted to the environment from the mining and industrial activities. Some of their ions are released to water environment such as acidic leachate from landfill^(1), 2). Adsorptive removal of these contaminants is one of the attractive options. Numerous numbers of adsorbents have been applied to remove heavy metal ions form water environment such as agricultural waste, industrial by-products, zeolite, clay and activated carbon^(3), 4). In general, carbonaceous materials including activated carbon exhibit excellent performance for adsorption of organic compounds, but they do not accommodate sufficient amount of heavy metal ions⁽⁵⁾. In case of using carbons as heavy metals adsorbents, carbon surface oxidation by air, ozone, hydrogen peroxide and nitric acid can be generally employed as effective methods to increase the amount of heavy metal adsorption at the expense of decrease in adsorption for organic compounds, because carboxyls and lactones introduced to carbon surface by oxidation can be effective adsorption sites for heavy metal ions, but the C-O complexes on the carbon reduce the π -electron density leading to

the significant reduction of organic compounds adsorption⁽⁵⁾. In contrast, complete removal of the C-O complexes from the carbon surface by out-gassing at 1173 K also results in the increase of adsorption capacities of heavy metal ions caused by C π -cation interaction⁽⁶⁾, and those of organic compounds will be enhanced though energy cost is increased by heating. On the other hand, metal oxides containing in or on the carbon can also be strong adsorption sites for heavy metal ions^(5), 7). Comparing to C-O complexes such as carboxyls and lactones which are strong electron withdrawing functional groups, the metal oxides are expected to affect a slight or no influence on the adsorption capacity of organic compounds because of holding the π electron density unchanged from the original graphene sheet. In our previous study, zinc oxides loaded activated carbon could enhance the lead (II) ion uptake by a factor of up to 4.5, operating electron static interaction between ZnO and Pb (II) ions, without decline of the amount of an organic compound adsorption^(5), 8). Stronger and greater adsorption sites for heavy metal ions will be required for activated carbon. Yantasee *et al.* examined the effect of carbon surface amine on adsorption of heavy metal ions, and found that introduction of $-NH_2$ onto activated carbon improved K_d , the distribution coefficient

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value, of copper (II) ions by 140 times greater than that measured on the unmodified activated carbon, whereas K_d was only 4 times greater for lead (II) at pH 5.8⁹). In the present study, influence of magnesium loading on lead (II) adsorption was inspected using activated carbon with various surface acidity. Meunier *et al.* pointed out that lead (II) uptake might be ion exchange with calcium, magnesium or potassium ions using high performance natural adsorbent of cocoa shells¹⁰. Similar ion exchange mechanism with calcium and magnesium was proposed for other naturally obtained adsorbents such as brown seaweed¹¹ and olive stone waste¹². In addition efficiency in removal of heavy metal ions of magnesium was considered to be preferable to calcium¹³.

2. Materials and methods

2.1 Adsorbents and their treatment and magnesium loading

Adsorbent used was commercially available granular activated carbon (GAC), namely Diasorb W10-30 made from coconuts shell, purchased from Cargon Mitsubishi Corporation. At first, ash contained was completely eliminated from GAC by sequentially washing in hydrochloric acid and fluoric acid to get rid of the influence of mineral matters for the heavy metal adsorption. The acid treated GAC was repeatedly boiled in de-ionized water until the solution pH at ambient temperature was not changed any more. In the next step, the de-ashed GAC was oxidized to introduce acidic oxygen groups onto the GAC surface, or out-gassed to completely remove them from the surface. The oxygen functional groups were carboxylic, lactonic and hydroxyl groups. The oxidation was carried out warming the mixture of nitric acid and de-ashed GAC controlling the temperature at 363 ~ 368 K. The oxidized GAC was rinsed for several times until a constant pH value was obtained, and then calcined at 653 K in air to decompose the nitric acid remaining in the carbon for 4 hours, and allowed to cool at room temperature in a desiccator. The amounts of the oxygen functional groups were altered changing the concentration of nitric acid and the warming time; for instance, GAC-Ox6.8-5 indicated that de-ashed GAC was oxidized with 6.8 M nitric acid for 5 hours. The out-gassing to thoroughly remove the acidic groups was done at 1173 K in helium flow. The de-ashed GAC was placed in a quartz tube, and high purity helium gas was slowly introduced to the quartz tube to prevent the carbon from scattering toward the down flow direction. When the most of the inner tube volume was sufficiently replaced by helium gas, the tube temperature was increased to 383 K for 10 minutes and kept for 5 minutes in an electric furnace to remove the extra air and moisture remaining inside the activated carbon particle, and then the furnace temperature was raised up to the out-gassing temperature up to 1173 K holding the temperature for 2 hours. In the final step, the quartz tube was removed from the furnace and cooled down to room temperature, kept helium flow

for 5 minutes before contact with air, and finally it was stored in a desiccator. The out-gassed carbons were donated as GAC-OG.

Five hundred mg-Mg/L of magnesium (II) nitrate solution was prepared, and 100 mL solution and 1.5 g of the de-ashed activated carbon of GAC, GAC-OG or GAC-OG-Ox of various acidic groups content was mixed in conical flask and agitated at 100 rpm and 298 K for 7 days. All chemicals used in the experiments were reagent grade. The magnesium (II) impregnated activated carbon was separated from the aqueous solution by vacuum filtration, rinsed with de-ionized water. After drying in air oven at 373 K, the activated carbon was calcined at 653 K for 4 hours to decompose nitrate ions as well. Only the calcined magnesium loaded GAC-OG was further out-gassed in helium flow at 1173 K to remove extra acidic functional groups formed by the calcination in air. The amount of magnesium loaded onto the activated carbons was measured by atomic absorption spectroscopy (AAS, Rigaku novAA 300) after dissolving the magnesium from the carbon by 1 M HCl.

2.2 Properties of the prepared adsorbents

The analytical characterization of the prepared activated carbon was made by N₂ adsorption-desorption at 77 K (Beckman Coulter Model 3100) and Boehm acid and base titration^{14, 15}. The BET surface area and pore size distribution were obtained from the N₂ adsorption using the *t*-plots numerical analysis. Surface acidic functional groups and basic sites were determined using the Boehm titration. For the magnesium loaded GAC-OG, prior to the determination of acidic functional groups, it was washed with HCl solution of pH 2, followed by out-gassed at 623 K in helium flow for 30 minutes.

A half gram of carbon and 15 mL of 0.1 M NaHCO₃, 0.05 M Na₂CO₃ or 0.1 M NaOH solution was mixed in conical flask, and agitated at 100 rpm for more than two days in room temperature. Five mL of the solution pipetted out for each sample was back titrated with 0.1 M HCl. The NaHCO₃ can neutralize only carboxylic groups on the carbon surface, Na₂CO₃ can react with both carboxylic and lactonic, and NaOH is able to react with all acidic groups of carboxyls, lactones and hydroxyls on the carbon. In accordance with the above assumption, the difference between the groups neutralized by NaHCO₃ and Na₂CO₃ becomes lactones, the difference between those neutralized by Na₂CO₃ and NaOH is hydroxyls. The same procedure was carried out for the mixture of 0.5 g of the carbons and 15 mL of 0.1 M HCl solution to determine the basic sites of the carbon surface. The remaining HCl solution was titrated with 0.1 M NaOH after neutralization. Neutralization points were monitored using methyl red solution indicator for weak base titrated with strong acid, and phenolphthalein solution for strong acid and strong base combination.

2.3 Adsorption measurements

Lead (II) ions were used as a heavy metal dissolving lead (II)

chloride to de-ionized water to adjust the concentration at 4.83 mmol/L for stock solution. The stock solution was diluted to desired concentration with de-ionized water. A hundred mg of the adsorbents was dosed to 50 mL of the aqueous solution, and agitated by 100 rpm for more than 5 days at 293 K for the equilibrium experiments. The solution pH was measured by a portable pH meter (HORIBA Model D-51) for the initial and the equilibrium solutions. Metal ions concentration of lead (II) and magnesium (II) in the solution was determined using atomic absorption spectroscopy (AAS) as described in the previous section. Prior to the AAS analysis, the solution was diluted with de-ionized water and a drop of 1 M HCl to the external standard concentration range. The HCl acid was added to convert all chemical species in the solution to Pb^{2+} or Mg^{2+} during the analysis for heavy metal ions.

Adsorption of an organic compound as well as heavy metal ions adsorption was also examined to compare the difference between with and without magnesium loading. Nitrobenzene was used as an organic compound because it was proven that its adsorption from aqueous solution was greatly influenced by surface nature and textural properties of activated carbons in our previous study¹⁶⁾.

3. Results and discussion

3.1 Properties of adsorbents

Total BET surface area, and those of meso- and macro-pore and micro-pore of de-ashed activated carbon, GAC, oxidized and out-gassed GAC's, and their magnesium modified counterparts were also tabulated in **Table 1**. Since the extent of oxidation was varied, one example of 7.5 M nitric acid oxidation for 8 hours is represented in the table as an oxidized activated carbon. As expected in the oxidation study, total BET surface area is clearly decreased by the introduction of C-O complexes to the edge of graphene sheet widening most of micro-pore into meso- and macro-pore⁵⁾. Though there is no significant difference between GAC and magnesium loaded GAC, a little activation effect of magnesium loading is observed in increasing micro-pore surface area for the out-gassed GAC. **Table 2** shows acidic functional groups and basic sites on

the activated carbon surface determined by Boehm titration. The more the HNO_3 concentration and oxidation time, the more the acidic functional groups are formed on the carbon surface. On the other hand, almost all carboxylic and lactonic groups are eliminated from the carbon surface by out-gassing at 1173 K, but some hydroxyl groups are remained on the surface.

3.2 Amount of magnesium loaded on GAC

As described in the previous section, the magnesium loaded to the activated carbons were prepared by calcining the magnesium (II)

Table 2 Surface acidic functional groups and basic sites by Boehm titration

Adsorbent	Carboxylic (-COOH), mmol/g	Lactonic (-COO-), mmol/g	Hydroxyl (-OH), mmol/g	Basic sites (C π), mmol/g
GAC	0.03	0.04	0.15	0.47
GAC-OG	0.00	0.00	0.08	1.10
GAC-OG-MgO-OG-AT	0.00	0.01	0.38	—
GAC-OG-Ox0.85-0.25	0.39	0.36	0.65	0.10
GAC-OG-Ox0.85-0.5	0.42	0.36	0.60	0.17
GAC-OG-Ox0.85-1	0.45	0.17	0.61	0.14
GAC-OG-Ox0.85-5	0.74	0.26	0.41	0.04
GAC-OG-Ox1.7-5	0.96	0.22	0.29	0.04
GAC-OG-Ox3.4-1	0.53	0.15	0.38	0.14
GAC-OG-Ox3.4-2.5	0.74	0.28	0.42	0.06
GAC-OG-Ox3.4-5	1.10	0.29	0.24	0.00
GAC-OG-Ox6.8-5	0.91	—	—	—
GAC-OG-Ox13.6-5	1.20	—	—	—

GAC : de-ashed coconuts shell granular activated carbon

GAC-Ox3.4-5 : GAC oxidized with 3.4 M HNO_3 for 5 hours

GAC-OG : GAC out-gassed at 1173 K

GAC-OG-MgO-OG-AT : magnesium loaded GAC-OG followed by out-gassing at 1173 K, and then washed with pH 2 acid solution

Table 1 BET specific surface area and pore distribution of adsorbents.

Adsorbent	BET specific surface area, m ² /g	Meso-&Macro- pore area, m ² /g	Micro-pore area, m ² /g
GAC	1120	120	1000
GAC-MgO	1120	130	990
GAC-Ox7.5-8	840	680	160
GAC-OG	1040	220	820
GAC-OG-MgO-OG	1190	150	1040

GAC : de-ashed coconuts shell granular activated carbon

GAC-MgO : magnesium loaded GAC

GAC-Ox7.5-8 : GAC oxidized with 7.5 M HNO_3 for 8 hours

GAC-OG : GAC out-gassed at 1173 K

GAC-OG-MgO-OG : magnesium loaded GAC-OG followed by out-gassing at 1173 K

Fig.1 Changes in the adsorption amount of magnesium(II) ions onto the de-ashed coconuts shell based activated carbons in aqueous solution as a function of the carboxyls amount on the carbon surface determined by Boehm titration.

ions pre-adsorbed carbons at 653 K. The amounts of loaded magnesium were depicted in **Fig.1** as a function of carboxyl groups, because the adsorption of divalent Mg^{2+} is principally considered to proceed via ion exchange with two carboxylic protons. The minimum point in **Fig.1** was observed at the carboxyls amount of around 0.2 mmol/g. Though the amount of magnesium is proportional to the carboxyl groups content above 0.2 mmol/g carboxyls, it is also increased by the very small amount of carboxyls below 0.2 mmol/g. Only a small amount of carboxylic is known to become sufficient amount for diminishing π electron density on the graphene sheet⁶⁾. Once the C-O complexes are thoroughly removed, the withdrawal π electron comes back to the graphite sheet, then interaction between π electron and magnesium(II) ions, namely $C\pi$ -cation interaction, is working instead of ion exchange process valid in the presence of carboxyls. The sharp increase in magnesium adsorption at the carboxyls amount approaching zero may be attributed to the increase in π electron density on the graphene sheet, since amount of basic sites reflecting $C\pi$ density is also increased by out-gassing as can be clearly seen in **Table 2**⁶⁾.

3.3 Influence of magnesium loading on Pb(II) adsorption

Influence of magnesium loading to activated carbon on Pb(II) ions adsorption was examined using de-ashed carbon of GAC, oxidized of GAC-Ox and out-gassed of GAC-OG. The solution pH was always less than 6.5 throughout the experiments, and most of the Pb(II) aqueous species in that pH range could be Pb^{2+} , but may be partly present as $Pb(OH)^+$ by the maximum 10 % at the

pH approaching 6.5. As shown in **Fig.2**, magnesium loading of GAC-MgO enhanced the Pb(II) adsorption obeying Langmuir isotherm as well as that without magnesium. The adsorption isotherm was come back to the original isotherm of GAC by washing GAC-MgO with 1 M HCl to remove loaded magnesium, revealing that the magnesium played an important role in Pb(II) adsorption. **Fig.3** represents the effect of magnesium loading onto oxidized carbon of GAC-Ox containing carboxylic groups about 1 mmol/g. As can be clearly seen, no enhancement of Pb(II) species was obtained by magnesium loading on GAC-Ox. The results suggested that the magnesium loading onto GAC-Ox and consecutive calcination, denoted to GAC-Ox-MgO, cannot change the magnesium chemical species, probably revealing that only ion exchanged Mg^{2+} species with carboxyl protons was formed on the carbon surface. In case of the magnesium loading to GAC-OG which was out-gassed at 1173 K in the final stage to remove acidic groups formed by the calcination in air at 653 K after magnesium loading, referred to as GAC-OG-MgO-OG, considerable enhancement of Pb(II) adsorption could be measured against the counterpart before magnesium loading of GAC-OG as drawn in **Fig.4**. The absolute amount of Pb(II) onto GAC-Ox indeed is greater than those onto GAC-OG irrespective of magnesium loading or not, but considerable reduction in adsorption amounts of organic compounds is necessarily observed for the oxidized GAC comparing to the non-oxidized carbon. Before the adsorption experiments, it was confirmed that no promoting effect could be observed for the Pb(II) adsorption onto the magnesium loading out-gassed GAC without calcination at

Fig.2 Pb(II) ions adsorption isotherms at 293 K before and after magnesium loading to the de-ashed activated carbon. ○ ; de-ashed activated carbon (GAC), ● ; magnesium loaded GAC (GAC-MgO), △ ; 1 M HCl washed GAC-MgO. Solid lines : predicted using Langmuir parameters obtained by experimental results.

Fig.3 Pb(II) ions adsorption isotherms at 293 K before and after magnesium loading to the activated carbon oxidized with nitric acid. ○ ; oxidized activated carbon (GAC-Ox), ● ; magnesium loaded GAC-Ox (GAC-Ox-MgO). Solid lines : predicted using Langmuir parameters.

653 K, suggesting that the magnesium species would be changed from C π -cation interaction to chemical binding to the carbon by the calcination. As drawn by the solid lines in **Figs.2** through **4**, the experimental results can be predicted by Langmuir isotherms as indicated below,

$$Q_e = \frac{K_e C_e}{1 + K_e C_e} X_m \dots \dots \dots (1),$$

where Q_e is the equilibrium amount of Pb(II) on the adsorbent, C_e is the equilibrium Pb(II) solution concentration, and K_e and X_m represent the Langmuir adsorption affinity and capacity, respectively. The K_e and X_m values calculated from the experimental plots are tabulated in **Table 3** for GAC, GAC-Ox and GAC-OG with and without magnesium loading. Though the adsorption capacities of X_m 's were not altered to much extent for all adsorbents by loading magnesium, the adsorption affinities of K_e 's were increased for GAC and GAC-OG, revealing that not the number but the quality of adsorption sites might be changed by magnesium loading. Particularly, the K_e value for GAC-OG-MgO-OG was

more than 20 times as great as that for GAC-OG. **Fig.5** shows the plots of the amount of magnesium(II) ions desorbed from the GAC-OG-MgO-OG against those of Pb(II) ions adsorbed onto the carbon. It can be suggested that the Pb(II) adsorption proceeds via ion exchange with magnesium(II) ions from the results, through the approximate line in **Fig.5** exhibits an intercept in the vertical axis revealing that a part of magnesium ions having no interaction to the carbon surface are released without the ion exchange with Pb(II) ions, probably due to magnesium remained without adsorption and/or separate from the surface in the GAC pore in the preparation procedure. When the GAC-OG-MgO-OG was washed with pH 2 nitric acid to remove the ion exchangeable magnesium(II), the remaining acidic sites are only hydroxyl groups as also represented in **Table 2** by GAC-OG-MgO-OG-AT, and the amount of phenolic groups was increased by 0.30 mmol/g comparing to GAC-OG, and the 0.30 mmol/g was more than equivalent amount of 0.2 mmol/g of 0.1 mmol/g magnesium(II) loading as seen in **Fig.1**. From these experimental results, the strong Pb(II) adsorption sites represented by K_e value 450 L/mmol can be supposed to be magnesium(II) bound to the edge of graphite carbon via oxygen bridge denoted to as C-O-Mg-O-C, in which "C" is represented as graphite carbon, though the hydroxyl groups by themselves cannot be effective.

For the de-ashed activated carbon of GAC with magnesium loading, the adsorption affinity of Pb(II) was more than five times greater than without magnesium. In our preliminary study, adsorption sites were considered to be able to be divided into two types for GAC; one is the acidic sites of carboxylic and lactonic groups, the other is

Fig.4 Pb(II) ions adsorption isotherms at 293 K before and after magnesium loading to the activated carbon out-gassed in helium at 1173 K. ○ ; out-gassed activated carbon (GAC-OG), ● ; magnesium loaded GAC-OG (GAC-OG-MgO). Solid lines : predicted using Langmuir parameters.

Table 3 Langmuir parameters for Pb(II) adsorption in aqueous solution

Adsorbent	X_m , mmol/g	K_e , L/mmol
GAC	0.04	16
GAC-MgO	0.06	59
GAC-Ox	0.24	47
GAC-Ox-MgO	0.25	37
GAC-OG	0.08	20
GAC-OG-MgO-OG	0.09	450

Fig.5 Relationship between Mg(II) ions released from magnesium loaded activated carbon (GAC-OG-MgO-OG) and Pb(II) adsorbed onto the carbon obtained by the adsorption kinetics experiments.

Fig.6 Nitrobenzene adsorption isotherms at 293 K before and after magnesium loading to the activated carbon out-gassed in helium at 1173 K. ○ ; out-gassed activated carbon (GAC-OG), ● ; magnesium loaded GAC-OG (GAC-OG-MgO). Solid lines : predicted using Langmuir parameters.

Table 4 Langmuir parameters for nitrobenzene adsorption in aqueous solution

Adsorbent	X_m , mmol/g	K_e , L/mmol
GAC-OG	2.8	20
GAC-OG-MgO-OG	2.7	22

basic sites caused by $C\pi$ electron on the graphene layer^{(6), (17)}. The adsorption affinity of Pb(II) onto GAC can be the average value of the acidic and basic sites. Based on the results on **Table 3**, magnesium ions adsorbed on basic sites of GAC are estimated to be converted from the $C\pi$ -cation to the stronger ion exchangeable C-O-Mg-O-C sites on the surface by the calcination, whereas those on acidic sites are no longer changed. The K_e value of 59 L/mmol might be, therefore, reflected by both acidic sites and C-O-Mg-O-C sites. The acidic sites are estimated to be principally working for Pb(II) ions adsorption on oxidized GAC-Ox-MgO, while only the newly introduced C-O-Mg-O-C strong sites can be operative for out-gassed GAC-OG-MgO-OG.

3.4 Influence of magnesium loading on nitrobenzene adsorption

Influence of magnesium(II) loading to activated carbon of GAC-OG on the adsorption of nitrobenzene was shown in **Fig.6** and **Table 4**. No significant difference between with and without magnesium was thankfully observed, even though strong adsorption sites for Pb(II) ions was developed on the carbon surface. In contrast to the magnesium loading, oxidation of activated carbon considerably reduced the adsorption capacity of aromatics forming

electron withdrawing functional groups of carboxyls and lactones on the carbon surface. It is generally accepted that the aromatic compounds adsorb on the non-oxidized graphitic part of the surface physically through dispersive interactions between the π electrons of the graphitic carbon basal planes and those of the aromatic ring, namely π - π dispersive force⁽¹⁸⁾⁻²⁰⁾. Decreasing π electron density on the graphene sheet, therefore, directly lead to the reduction of aromatics adsorption⁽²¹⁾. Consequently, magnesium loading affected no influence on π electrons density of the carbon at all. Based on the experimental results of the adsorption of the heavy metal ions and aromatics, it can be concluded that the strong adsorption sites for Pb(II) adsorption are generated on the activated carbon by calcining $C\pi$ -magnesium(II) cation species at 653 K in air without any significant decline in adsorption capacity of the aromatic compound.

4. Summary

Influence of magnesium(II) loading to coconuts shell based activated carbons possessing various surface oxygen heterogeneity on the adsorption of Pb(II) ions and nitrobenzene in aqueous solution. The following conclusions might be deduced to summarize the experimental results.

- 1) The amounts of surface oxygen acidic groups can be controlled by changing nitric acid concentration and oxidation time.
- 2) Oxidation of the activated carbon increase the adsorption amount of magnesium(II) ions being proportional to carboxyl groups, but out-gassing also enhance the adsorption. The ion exchange with carboxyl protons can be working in the former, but the $C\pi$ -cation interaction shall be operative for the latter.
- 3) Introducing magnesium(II) ions onto the activated carbon by impregnation in aqueous solution followed by calcination at 653 K, the Langmuir adsorption affinity of Pb(II) ions was enhanced more than 20 times as great as that without magnesium loading for the activated carbon out-gassed in helium at 1173 K, whereas there was no effect of magnesium loading for the oxidized activated carbon.
- 4) Pb(II) adsorption for the magnesium loading out-gassed activated carbon would proceeded by ion exchange mechanism, because the equivalent amount of magnesium ions was released into aqueous solution in the process of Pb(II) ions adsorption.
- 5) The strong adsorption sites for Pb(II) ions were estimated to be made up of magnesium(II) binding to graphite carbon via oxygen bridge since only hydroxyl groups can be detected by Boehm titration after acid washing the magnesium loaded carbon.
- 6) No influence of magnesium loading on adsorption of organic compounds might be expected, because the adsorption isotherms of nitrobenzene were not varied at all by the introduction of magnesium onto out-gassed activated carbon.

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