

$y$	= distance from wall surface	[m]
$\Gamma$	= mass flow rate of liquid per unit perimeter	[kg/m·s]
$\theta$	= angle of inclination of wetted-wall plate	[degree]
$\mu$	= liquid viscosity	[Pa·s]
$\rho$	= liquid density	[kg/m <sup>3</sup> ]

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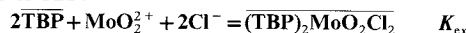
## EXTRACTION OF MOLYBDENUM AND VANADIUM FROM HYDROCHLORIC ACID BY TRI-*n*-BUTYL PHOSPHATE IN VARIOUS DILUENT SOLUTIONS

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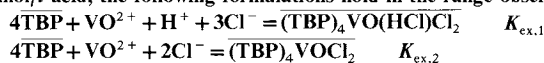
**Key Words:** Chemical Equilibrium, Metal Extraction, Diluent Effect, Solvation, Tri-*n*-butyl Phosphate, Molybdenum, Vanadium, Electron Donor, Electron Acceptor

The mechanism of extraction was studied, employing several diluents with differing electron-accepting properties. For molybdenum, from 3–7 mol/l acid, the following formulation holds for all diluents and over the whole range of loading ratio of TBP.



The extraction constants are 4.42 for *n*-heptane, 1.50 for xylene and 0.0114 for chloroform at low loading. They start to decrease sharply at medium and high loading. This is caused by the variation of properties of the organic solution due to the presence of the excessive amount of organic molybdenum.

For vanadium, from 2–5 mol/l acid, the following formulations hold in the range observed.



The constants are  $K_{\text{ex},1} = 1.41 \times 10^{-5}$  and  $K_{\text{ex},2} = 9.19 \times 10^{-5}$  in xylene diluent. They remain constant in the range of normal operation, since the extractability of TBP for this metal is very low.

### Introduction

Tri-*n*-butyl phosphate is an established extractant which acts by the solvation of neutral inorganic molecules or complexes by electron donorship of the phosphoryl group. It has been widely used in the nuclear field and an enormous accumulation of experimental data for non-nuclear and nuclear metals is available, as reviewed and discussed by Ritcey.<sup>13)</sup> Despite this, the systems are complex, with few easily definable species as discussed by Ritcey and Ashbrook<sup>14)</sup> and Sekine and Hasegawa.<sup>18)</sup> Generalized relationships for the extraction of metals

by TBP are therefore extremely difficult to formulate.

To evaluate the effect of diluent on extraction, several studies have been carried out on the basis of the activity coefficients of TBP and the resulting uranium complex, as measured by aqueous distribution of <sup>32</sup>P-labelled TBP and by the vapor isopiestic method, respectively.<sup>3,12,15,19)</sup> It has been found that the activity coefficients are much smaller than 1 in diluents such as chloroform and higher alcohols, slightly greater than 1 in diluents such as benzene and carbon tetrachloride, and much greater than 1 in *n*-hexane and *n*-octane. However, in these studies the metal species was limited to uranium nitrate and the effect of diluent was examined using data measured only at fixed experimental conditions.

For the extraction of molybdenum by TBP, the

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composition of the extract from the nitrate media was found to be  $(\text{TBP})_2\text{MoO}_2(\text{NO}_3)_2$ . This was found by an isomolar series method at limited conditions of aqueous acidity.<sup>2)</sup> For vanadium, the molecular ratio of TBP to metal in the extract was found to be 2:1 by a slope analysis of the distribution curves. This is, however, limited to an organic solution containing TBP greater than 0.35 mol/l and to an aqueous solution containing 10 mol/l LiCl and 0.06 mol/l HCl.<sup>17)</sup>

In the present work, measurements of the extraction of molybdenum and vanadium by TBP in various diluents were made and the corresponding extraction equilibria formulated. These two metals were chosen since a study on recovery of the two metals from desulfurization waste catalyst and oil boiler slag had been carried out.<sup>6)</sup> The diluents were chosen to furnish a wide range of characteristics of TBP, i.e., *n*-heptane, xylene and chloroform.

## 1. Experiments

### 1.1 Solutions

TBP, kindly supplied by Daihachi Chemicals Ind. Co., Ltd., Osaka, with a purity of approximately 99%, was further purified, following the procedure of Peppard.<sup>11)</sup> Working solutions were made by diluting the purified TBP with the appropriate diluent.

Stock solutions of molybdenum were prepared by dissolving sodium molybdate,  $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$ , in distilled water and were standardized by EDTA titration using PAN as an indicator.<sup>21)</sup> Stock solutions of vanadium were prepared by dissolving sodium metavanadate,  $\text{NaVO}_3$ , in warm distilled water with constant stirring and were standardized by EDTA titration using PAN as an indicator.<sup>21)</sup> Stock solutions of hydrochloric acid were adjusted to 10 mol/l and working solutions were prepared volumetrically from these stocks.

The inorganic chemicals and the diluents, *n*-heptane, xylene and chloroform, were supplied by Wako Chemical Ltd., as analytically pure reagent grade.

### 1.2 Procedures

Equal volumes of an organic and aqueous solutions were shaken for 3 hr in a thermostat bath at  $25 \pm 0.1^\circ\text{C}$ . After the two phases had been allowed to settle for 6 hr, they were separated. For molybdenum, a weighed organic sample was stripped with water and the resulting aqueous sample was analysed for molybdenum at 313.3 nm using a Jarrell Ash 702 atomic absorption spectrophotometer. For vanadium, hydrochloric acid of 0.1 mol/l was used as stripping solution and analysed at 306.6 nm. Procedures used for the analysis of water, hydrogen ion and chloride ion in the organic phase are described in the previous work.<sup>7)</sup>

The IR spectra of the organic solution containing

TBP and molybdenum extract were obtained with a Hitachi 260-10 IR spectrophotometer and 0.1 mm NaCl cell at  $23\text{--}25^\circ\text{C}$ .

The concentration of TBP in the organic feed solution was in the range of  $5 \times 10^{-2}$ – $7 \times 10^{-1}$  mol/l for molybdenum and  $5 \times 10^{-1}$ – $2 \times 10^0$  mol/l for vanadium. The concentration of molybdenum in the aqueous feed solution was in the range of  $4 \times 10^{-4}$ – $10^0$  mol/l, and for vanadium  $10^{-3}$ – $5 \times 10^{-1}$  mol/l. The concentration of hydrochloric acid varied up to 10 mol/l, and was mostly 3–6 mol/l for molybdenum and 2–5 mol/l for vanadium.

For the extraction of molybdenum, the three solvents, *n*-heptane, xylene and chloroform, were employed as diluents. For vanadium, however, only xylene was employed. This was because preliminary studies showed the extractability of TBP for this metal to be much less than for molybdenum.

## 2. Results

### 2.1 Extraction equilibria for Mo(VI) at low loading of the organic phase

The method of slope analysis is applicable to the data obtained at low loading of the organic phase and for which the concentration change of TBP is negligible. The main molybdenum species, under the conditions of the present acid concentration, was found to be hexavalent,  $\text{MoO}_2$ .<sup>16)</sup> Assuming that this is extracted as a *y*-merized complex of the composition, the overall extraction can be described by the general equation

$$\begin{aligned} x\overline{\text{TBP}} + y\text{MoO}_2^{2+} + (z-2y)\text{H}^+ + z\text{Cl}^- \\ = (\text{TBP})_x(\text{MoO}_2)_y(\text{H})_{z-2y}(\text{Cl})_z \\ K_{\text{ex}} = \frac{[(\text{TBP})_x(\text{MoO}_2)_y(\text{H})_{z-2y}(\text{Cl})_z]}{[\overline{\text{TBP}}]^x[\text{MoO}_2^{2+}]^y[\text{H}^+]^{z-2y}[\text{Cl}^-]^z} \end{aligned} \quad (1)$$

The distribution ratio of molybdenum is given by

$$\begin{aligned} D_{\text{Mo}} &= [\overline{\text{MoO}_2}]/[\text{MoO}_2^{2+}] \\ &= y[(\text{TBP})_x(\text{MoO}_2)_y(\text{H})_{z-2y}(\text{Cl})_z]/[\text{MoO}_2^{2+}] \end{aligned} \quad (2)$$

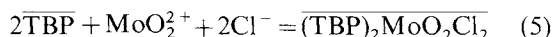
which leads to

$$[\overline{\text{MoO}_2}] = yK_{\text{ex}}[\overline{\text{TBP}}]^x[\text{MoO}_2^{2+}]^y[\text{H}^+]^{z-2y}[\text{Cl}^-]^z \quad (3)$$

The slope of  $[\overline{\text{MoO}_2}]$  against  $[\text{MoO}_2^{2+}]$  at constant concentration of TBP and aqueous acidity gives the degree of association of organic molybdenum extract. Straight lines with a slope of 1 were obtained, indicating the extract to be monomeric and thus  $y=1$ . The distribution ratio can then be simplified to

$$D_{\text{Mo}} = K_{\text{ex}}[\overline{\text{TBP}}]^x[\text{H}^+]^{z-2}[\text{Cl}^-]^z \quad (4)$$

The variation of  $D_{\text{Mo}}$  with concentration and mean ionic activity of hydrochloric acid,  $a_{\text{H}}$ , at constant TBP concentration is shown in Fig. 1 for the xylene diluent system. The mean ionic activity is defined as  $(m_{\pm} \gamma_{\pm} d_o)$ , where  $m_{\pm}$ : molality of acid,  $\gamma_{\pm}$ : mean ionic activity coefficient and  $d_o$ : specific gravity at 25°C. The activity was obtained, using literature data.<sup>10)</sup> With increasing acid concentration the ratio rises rapidly, attaining a maximum at 8–9 mol/l, and then decreases. A straight line with a slope of 2 is obtained for acid concentrations up to 7 mol/l, and thus  $z=2$ . The variation of the ratio values of  $D_{\text{Mo}}/a_{\text{H}}^2$  with  $[\text{TBP}]$  is shown in Fig. 2. Straight lines with a slope of 2 are obtained for all diluent systems, and thus  $x=2$ . The overall extraction equilibrium may be expressed as follows.



The extraction constant is determined as 4.42 for *n*-heptane, 1.50 for xylene and as low as  $1.14 \times 10^{-2}$  for the chloroform diluent system.

When the diluent molecule acts as an electron-acceptor, it interacts with an active oxygen atom of the phosphoryl group of TBP, effectively reducing the latter's concentration and so decreasing the extraction performance. The donor number of TBP has been determined as 23.7, and the acceptor number 0.0 for *n*-hexane, 8.2 for benzene and 23.1 for chloroform.<sup>5)</sup> The present result on the effect of diluent, therefore, seems to be quite reasonable.

Several series of runs were made, where equilibrium organic molybdenum concentration was increased. The apparent extraction constants obtained on the basis of Eq. (5) are plotted against loading ratio in Fig. 3. The values remain constant up to a loading ratio of 0.10 for *n*-heptane and xylene and 0.005–0.01 for chloroform, and then decrease sharply. In contrast, in the case of metal extraction by acidic organophosphorus compounds a sharp increase in the apparent extraction constant was encountered at high loading of the organic phase.<sup>8)</sup> In the case of cobalt extraction by quaternary ammonium chloride dissolved in benzene, the fraction of aggregated (dimeric) cobalt extract species increased with cobalt loading.<sup>9)</sup>

### 2.2 Extraction equilibria for Mo(VI) at high loading of organic phase

The sharp decrease in the apparent extraction constant may be caused either by variation of the formulation from Eq. (5) or by variation of the organic activity coefficients at high loading. The analytical composition of the extract entities was investigated at high loading and compared with the results obtained at low loading using a slope analysis method.

The amount of chloride ion co-extracted with molybdenum,  $\Delta[\text{Cl}]$ , was determined from the ob-

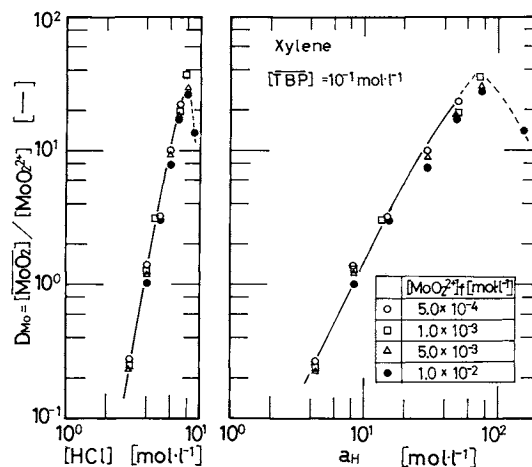


Fig. 1. Effect of concentration and mean ionic activity of hydrochloric acid on the distribution ratio of molybdenum. Comparison of observed data with prediction shown by solid lines.

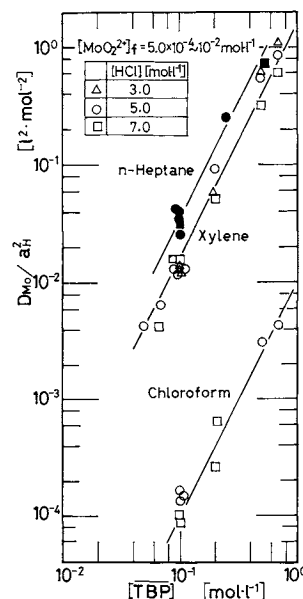


Fig. 2. Effect of TBP concentration on normalized distribution ratio of molybdenum.

served organic chloride concentration, corrected for the contribution of acid extracted by TBP and dissolved in each diluent. This contribution was determined by measuring the organic hydrogen ion concentration. The ratios  $\Delta[\text{Cl}]/[\text{MoO}_2]$  are plotted against loading ratio in Fig. 4, indicating molybdenum to be extracted in the form of  $\text{MoO}_2\text{Cl}_2$  over the whole range of loading ratios.

The loading ratios are plotted against aqueous feed concentration of molybdenum for the series of conditions with  $[\text{TBP}]_f = 10^{-1} \text{ mol/l}$  in Figs. 5(a) and (b). At low aqueous feed concentrations, a proportional relationship is observed, as expected from the results in the preceding section. At high concentrations, the ratio attains a limiting value of 0.5 for *n*-heptane and xylene diluents, and indicates the ratio of TBP to

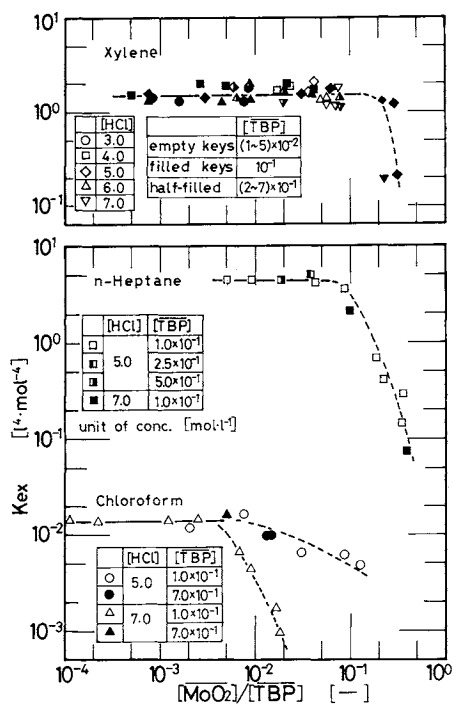


Fig. 3. Variation of extraction constant for molybdenum with loading ratio of TBP.

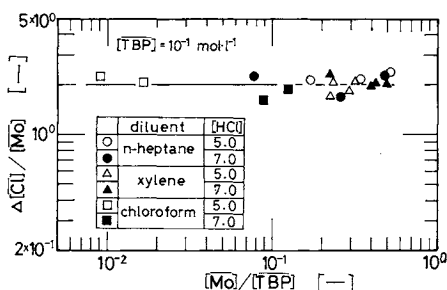
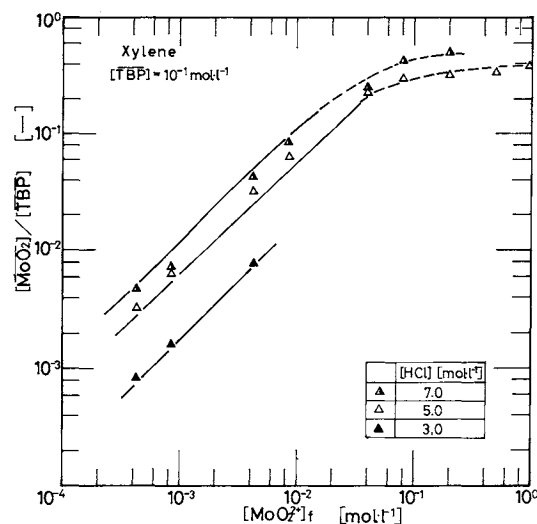


Fig. 4. Molecular ratio of chloride ion to molybdenum in the extracted species.

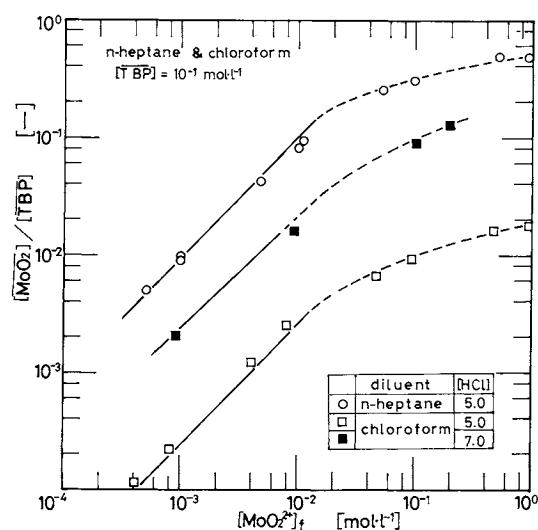
molybdenum to be 2:1 at the extreme conditions of maximum loading of TBP.

Consequently, the composition of organic extract is solely  $(TBP)_2MoO_2Cl_2$  over the whole range from low loading to maximum loading. The apparent form of the formulation, Eq. (5), holds up to high loading, but the extraction constant is reduced very much at high loading.

The results of the IR spectra of the solutions are tabulated in Table 1. For the solution with no molybdenum loading, there is a tendency for the phosphoryl absorption peak to shift toward a lower frequency in diluents with greater electron-accepting properties, as found previously by Ferraro.<sup>4)</sup> For the solutions with molybdenum loading, the peak is seen to shift toward lower frequency with molybdenum loading. This suggests that the uncomplexed phosphoryl group may possibly have interacted with organic molybdenum extract. The organic activity coefficients will thus be



(a)



(b)

Fig. 5(a) and (b). Variation of loading ratio of TBP with aqueous feed concentration of molybdenum. Comparison of observed data with prediction shown by solid lines.

affected by the metal concentration. The presence of a large concentration of organic metal is likely to change the properties of the organic solution from those of TBP in a diluent to those of some new substance with much poorer extraction performance. The system employing chloroform as a diluent has shown very much reduced resistance to the presence of organic molybdenum as shown in Fig. 3. This is probably due to the interaction between the parent TBP molecule with the chloroform via hydrogen-bonding.<sup>12,17)</sup>

### 2.3 Extraction equilibria for V(IV)

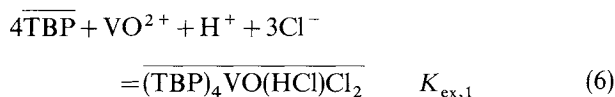
The aqueous vanadium species in 1–6 mol/l HCl solution has been found to exist as tetravalent  $VO^{2+}$  by the analysis of ESR spectra of frozen samples,<sup>6)</sup> in contrast with the result of Tedesco and deRumi<sup>20)</sup> who considered it to be pentavalent. The slope anal-

**Table 1.** Variation of phosphoryl absorption peak with diluent employed and molybdenum loading

<i>n</i> -Heptane		Xylene		Chloroform	
[Mo]/[TBP]	$\nu$ (cm <sup>-1</sup> )	[Mo]/[TBP]	$\nu$ (cm <sup>-1</sup> )	[Mo]/[TBP]	$\nu$ (cm <sup>-1</sup> )
0	1286, 1271	0	1282, 1266	0	1255
$2.48 \times 10^{-2}$	1282, 1265	$2.14 \times 10^{-2}$	1280, 1265	$3.50 \times 10^{-2}$	1253
$5.0 \times 10^{-1}$	1208	$5.0 \times 10^{-1}$	1205	$2.39 \times 10^{-2}$	1248

ysis method is applied to determine the extraction equilibrium formulation. When plotting the organic vanadium concentration,  $[\overline{\text{VO}}]$ , against aqueous feed,  $[\text{VO}^{2+}]_f$ , at constant TBP concentration and aqueous acidity, straight lines with a slope of 1 were obtained in the range of loading ratio less than 0.08–0.10. The extract is therefore monomeric. In this system, however, the loading ratio of TBP in xylene can exceed 0.08–0.10 under special conditions only, since the extraction performance for vanadium is very low. The distribution ratios are plotted against the concentration and mean ionic activity of hydrochloric acid in **Fig. 6**. A straight line with a slope of 3 against activity is seen for the data obtained with  $[\text{VO}^{2+}]_f$  less than  $10^{-1}$  mol/l at  $[\text{HCl}] = 2\text{--}5$  mol/l.

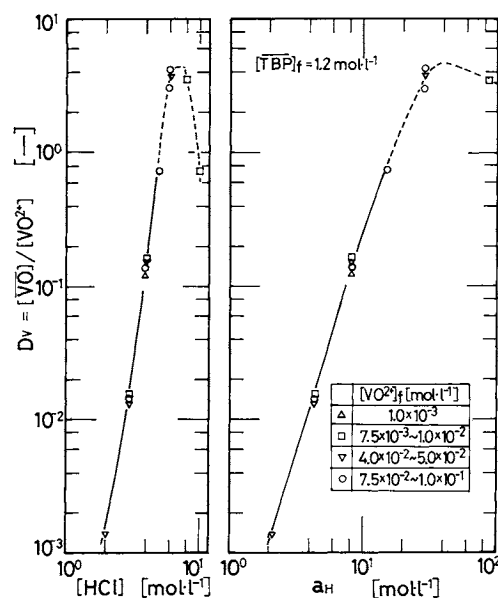
The distribution ratios were plotted against TBP concentration. For the data obtained with  $[\text{HCl}] = 6$  mol/l, the ratios are proportional to the 2nd power of TBP concentration, as shown in **Fig. 7(a)**, indicating the molecular ratio of TBP to vanadium in the extract to be 2:1. This value is in accordance with that of Sato *et al.*,<sup>17)</sup> obtained under a series of conditions with  $[\text{LiCl}] = 10$  mol/l and  $[\text{HCl}] = 0.06$  mol/l for benzene diluent. This value is also similar to a value of 2.7:1 obtained using the isomolar series method at  $[\text{HCl}] = 6$  mol/l for carbon tetrachloride solution.<sup>20)</sup> The data obtained with  $[\text{HCl}] = 2\text{--}5$  mol/l are, however, proportional to the 4th power of TBP concentration as shown in **Figs. 7(a) and (b)**. Accordingly, for the range of  $[\text{HCl}] = 2\text{--}5$  mol/l, the following extraction scheme can now be made.



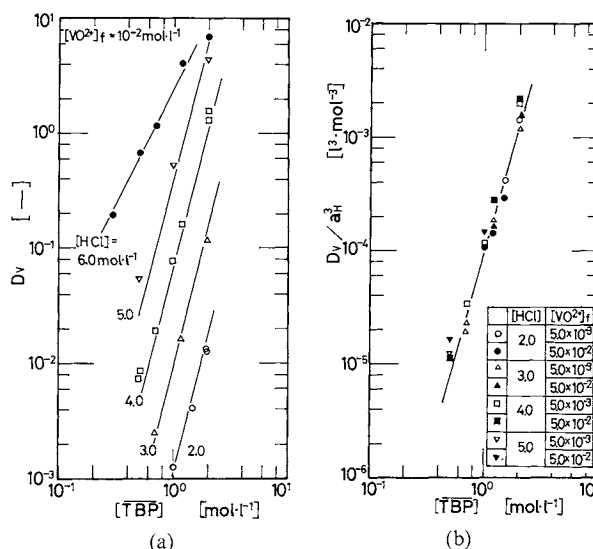
The material balances for TBP and vanadium extract are expressed, respectively, as follows.

$$\begin{aligned} [\overline{\text{TBP}}] &= [\overline{\text{TBP}}]_{\text{uncom}} \\ &+ 4\{[(\overline{\text{TBP}})_4\overline{\text{VO}}(\text{HCl})\text{Cl}_2] + [(\overline{\text{TBP}})_4\overline{\text{VOCl}}_2]\} \\ &= \delta + 4[\text{VO}^{2+}]a_{\text{H}}^2(K_{\text{ex},1}a_{\text{H}}^2 + K_{\text{ex},2})\delta^4 \end{aligned} \quad (8)$$

$$\begin{aligned} [\overline{\text{VO}}] &= [(\overline{\text{TBP}})_4\overline{\text{VO}}(\text{HCl})\text{Cl}_2] + [(\overline{\text{TBP}})_4\overline{\text{VOCl}}_2] \\ &= [\text{VO}^{2+}]a_{\text{H}}^2(K_{\text{ex},1}a_{\text{H}}^2 + K_{\text{ex},2})\delta^4 \end{aligned} \quad (9)$$



**Fig. 6.** Effect of concentration and mean ionic activity of hydrochloric acid on distribution ratio of vanadium. Comparison of observed data with prediction shown by solid line.



**Fig. 7(a) and (b).** Effect of TBP concentration on distribution ratio of vanadium.

where  $\delta$  denotes the concentration of free (uncomplexed) TBP,  $[\overline{\text{TBP}}]_{\text{uncom}}$ . The most probable values of  $K_{\text{ex},1}$  and  $K_{\text{ex},2}$  were estimated to minimize the sum of squares of the residuals based on Eqs. (8) and (9) for

all runs obtained with  $[HCl] = 2-5 \text{ mol/l}$ . The values thus estimated were  $K_{ex,1} = 1.41 \times 10^{-5}$  and  $K_{ex,2} = 9.19 \times 10^{-5}$ . The predicted values of  $D_V$  and  $[VO]/[TBP]$  are shown with solid lines in Fig. 6 and Fig. 8, and compared with observed values. All the data obtained with  $[VO^{2+}]_f$  up to  $5 \times 10^{-1} \text{ mol/l}$  are correlated satisfactorily by this formulation.

To confirm the present scheme given by Eqs. (6) and (7), the determination of the quantity of chloride ion associated with vanadium extract was attempted. A measurement of organic hydrogen ion was needed to correct for the contribution of HCl associated with uncomplexed TBP and dissolved in xylene. This was unfortunately impossible, since the hydrolysis reaction,  $VO^{2+} + OH^- = VOOH^+$ , occurred when sodium hydroxide was added. As an alternative, an indirect method was employed. The amount of acid associated with uncomplexed TBP in the molybdenum extraction was estimated from the data obtained for the acid extraction by TBP with no metal loading.<sup>6)</sup> The observed values thus corrected,  $\Delta[Cl]/[VO]$ , exhibited scatter between 2.3 and 2.6. The predicted values based on Eqs. (6) and (7) were between 2.8 and 3.0. No ready explanation is available for this small deviation.

### 3. Discussion

TBP extracts both water and inorganic acids when equilibrated with acid solution. The role of water and acid associated with TBP has been ignored in the present extraction formulation. However, there is an argument that water is likely to have a role in the mechanism of metal extraction, since the amount of water in the organic TBP solution has been found to vary by the loading of metals.<sup>1,20)</sup> High concentration of hydrochloric acid in the organic phase, if present, was found to have little effect on the observed spectra of TBP in benzene.<sup>17)</sup> This indicates that TBP molecules in a diluent are not significantly stabilized by acid molecules.

A series of runs for input of  $[TBP] = 1.10 \times 10^{-1} \text{ mol/l}$  and  $[HCl] = 5 \text{ mol/l}$  was carried out in which the amount of water associated with uncomplexed and complexed TBP molecules was measured. The water content,  $[H_2O]_f$ , had been corrected for the contribution of water uptake by xylene diluent alone ( $2.19 \times 10^{-2} \text{ mol/l}$  at  $[HCl] = 5 \text{ mol/l}^{17)}$ , assuming the value to be unchanged by the presence of TBP and organic molybdenum. The amount of water associated with uncomplexed TBP,  $[H_2O]_{uncom}$ , is  $2.7 \times 10^{-2} \text{ mol/l}$  under the conditions considered, and thus the molecular ratio,  $[H_2O]_{uncom}/[TBP]_{uncom}$ , is  $2.7 \times 10^{-2}/1.1 \times 10^{-1} = 0.245$ . The data of water content,  $[H_2O]_f$ , are plotted against loading ratio in Fig. 9. The amount of water associated with complexed TBP is then calculated by the relation of  $[H_2O]_{Mo} = [H_2O]_f$

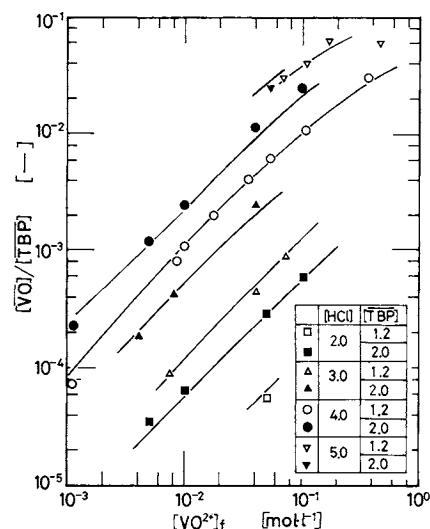


Fig. 8. Variation of loading ratio of TBP with aqueous feed concentration of vanadium. Comparison of observed data with prediction shown by lines.

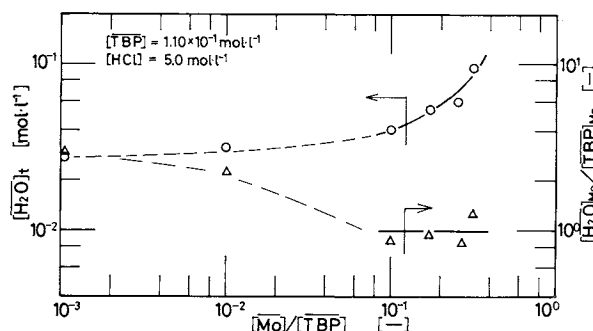


Fig. 9. Variation, with progress of molybdenum extraction, of amount of water associated with TBP and of molecular ratio of water to molybdenum in the extract entity.

$-0.245[TBP]_{uncom}$ . The ratio,  $[H_2O]_{Mo}/[TBP]_{Mo}$ , is plotted in Fig. 9. The ratio is seen to scatter around a value of 1 at high loading ratio. The data obtained at low loading were not reproducible owing to a small difference between  $[H_2O]_f$  and  $[H_2O]_{uncom}$ , and have therefore been neglected. Consequently, the amount of water associated with complexed TBP is not significantly different from that for uncomplexed TBP. This is one of the possible reasons that the role of water in the extraction equilibrium formulation can be ignored in the present study.

### Conclusion

The extraction of molybdenum and vanadium by TBP from hydrochloric acid was studied, with the following results.

1) The mechanism of extraction for molybdenum from 3-7 mol/l acid is expressed by Eq. (5) for all diluents employed. The extraction constants at low loading of TBP are 4.42 for *n*-heptane, 1.50 for xylene and as low as  $1.14 \times 10^{-2}$  for chloroform diluent system. The variation of the constant with diluent

employed is reasonably explained by the electron-accepting characteristics of each diluent.

2) The apparent form of the relation, Eq. (5), holds over the whole range of loading of TBP. Despite this the extraction constant remains constant up to a loading ratio of 0.10 for *n*-heptane and xylene, and up to 0.005–0.01 for chloroform, and then starts to decrease sharply. This decrease is caused by variation of the properties of the organic solution due to the presence of excessive concentrations of organic molybdenum for each diluent.

3) The mechanism of extraction for vanadium from 2–5 mol/l acid is expressed by Eqs. (6) and (7). The extraction constants are  $1.41 \times 10^{-5}$  and  $9.19 \times 10^{-5}$ , respectively, in xylene diluent. They remain constant in the range of normal operation, since the extraction performance for this metal is very low.

#### Acknowledgment

The present authors gratefully acknowledge the financial support of Grant-in-Aid for Developmental Scientific Research (No. 59850155, 1984) from the Ministry of Education, Science and Culture of Japan, and the experimental assistance of Mr. M. Kobayashi. The TBP was kindly supplied by Daihachi Chemicals Ind. Co., Ltd., Osaka.

#### Nomenclature

$a_H$	= mean ionic activity of hydrochloric acid [mol·l <sup>-1</sup> ]
$\Delta[Cl]$	= amount of chloride ion accompanied by metal extraction and associated with organic metal [mol·l <sup>-1</sup> ]
$D_{Mo}(=[\overline{MoO_2}]/[MoO_2^{2+}])$	= distribution ratio of molybdenum [—]
$D_V(=[\overline{VO}]/[VO^{2+}])$	= distribution ratio of vanadium [—]
$[H_2O]_{Mo}$	= amount of water associated with complexed TBP [mol·l <sup>-1</sup> ]
$[H_2O]_t$	= amount of water associated with complexed and uncomplexed TBP [mol·l <sup>-1</sup> ]
$[H_2O]_{uncom}$	= amount of water associated with uncomplexed TBP [mol·l <sup>-1</sup> ]
$[TBP]_{uncom}(=\delta=[\overline{TBP}]-2[\overline{Mo}])$	= concentration of uncomplexed TBP [mol·l <sup>-1</sup> ]
[ ]	= concentration of species in brackets [mol·l <sup>-1</sup> ]
$\delta(=[\overline{TBP}]_{uncom})$	[mol·l <sup>-1</sup> ]
<Subscript>	
<i>f</i>	= feed value
<Superscript>	
—	= organic phase species

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(Presented in part at the 17th Autumnal Research Meeting of The Society of Chemical Engineers, Japan at Sendai, Oct. 1, 1983, and at Symposium on Solvent Extraction at Tokyo, Dec. 5, 1985.)