Title
COMBINED SOLVENT EXTRACTION AND STRIPPING FOR REMOVAL AND ISOLATION OF AMMONIA FROM SOUR WATERS

Permalink
https://escholarship.org/uc/item/23q4s65p

Authors
Mackenzie, P.D.
King, C.J.

Publication Date
1984-06-01
COMBINED SOLVENT EXTRACTION AND STRIPPING FOR REMOVAL AND ISOLATION OF AMMONIA FROM SOUR WATERS

P.D. Mackenzie and C.J. King

June 1984

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks.

APPLIED SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098
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.
COMBINED SOLVENT EXTRACTION AND STRIPPING FOR REMOVAL AND ISOLATION OF AMMONIA FROM SOUR WATERS

by
Patricia D. Mackenzie & C. Judson King
Lawrence Berkeley Laboratory & Department of Chemical Engineering
University of California, Berkeley CA 94720

ABSTRACT
Simultaneous stripping and solvent extraction offer the possibility of removing and isolating ammonia from sour waters with less steam consumption. Liquid cation exchangers were found to be effective for extraction of ammonia under those conditions. Among the liquid cation exchangers considered, di-2-ethylhexyl phosphoric acid (D2EHPA) appeared to have the most favorable properties. Addition of modifiers to diluents for D2EHPA profoundly affects a number of important solvent properties and affords an avenue toward solvent improvement. Acid modifiers, such as alcohols, phenols, and carboxylic acids, solvate the D2EHPA-ammonium ion pair and thereby increase the degree of extraction of ammonia, reduce aqueous-solubility losses of D2EHPA, improve phase-separation properties, and decrease the volatility of ammonia upon solvent regeneration. Basic amine modifiers complex with D2EHPA, and thereby decrease the degree of ammonia extraction, reduce aqueous-solubility losses of D2EHPA, and increase the volatility of ammonia upon solvent regeneration. These effects have been demonstrated and interpreted through complexation models. Preliminary cost analyses indicate that the dominant factors are steam costs for solvent regeneration and costs of replacing extractant lost by aqueous solubility.

INTRODUCTION
In many industrial applications volatile weak acids, such as CO₂ and H₂S, and weak bases, such as NH₃, are present in significant quantities in wastewater. Condensate waters from coal-conversion processes can contain all three of these components at a pH around 7.5 to 9.5 (King, et al, 1981). Petroleum-refinery sour waters typically contain NH₃ and H₂S at pH about 7.5 (Darton, et al, 1978). Energy requirements for removing these contaminants by ordinary steam stripping can be large, requiring a boil-up of 10 to 20% of the feed water, depending on the degree of ammonia removal required. It is often desired to isolate the individual components, in order to sell the ammonia
and/or to send the H$_2$S to a Claus plant. This is even more energy intensive. For example, the Phosam-W and the "all-distillation" processes require boil-ups of between 25 and 35% of the feed water (Seufert, et al., 1979). These high steam requirements result from the interaction between the acidic and basic components, suppressing the volatilities. At the pH of the wastewaters, NH$_3$, CO$_2$ and H$_2$S are largely ionized. Only the un-ionized form is volatile, so the presence of the base serves to decrease the volatility of the acid and vice versa.

To save energy in the treatment of these wastewaters it would be desirable to strip the acid gases from solution at low pH. But in order to do this a second mechanism, or separation process, must be employed to remove ammonia under these conditions. Cahn, et al. (1978) originally proposed such a combined process. They suggest using liquid-membrane extraction to remove ammonia and steam stripping to remove the acid gases, a combined process which they call "extripping."

In the current work combining solvent extraction with steam stripping is investigated. One possible implementation of this process is shown in Figure 1. The wastewater enters the stripper, and a fraction of the acid gases is removed. As a result the pH rises. The partially stripped water is then sent to an extractor in which ammonia is extracted. This lowers the pH. This water is then returned to the stripper for further CO$_2$ and H$_2$S removal. This stripping/extraction may be repeated as often as needed. The net effect is that desired; the acid gases are stripped from solution at a low pH. The solvent which leaves the extractor loaded with ammonia is regenerated by stripping at elevated temperature and/or low pressure. Ammonia is thus isolated from the acid gases. Other flow configurations for implementing this approach are also possible.
The key to this process is to identify a suitable solvent. The solvent should (1) have a high capacity and selectivity for either the basic or acidic components, (2) result in low solvent losses to the aqueous phase through solubility losses and/or incomplete phase separation, (3) be easily regenerable and release the extracted solute in salable form, (4) have reasonable viscosity and density, and (5) be inexpensive and commercially available.

The goals of the current work were (1) to identify solvents that meet the above requirements and to study experimentally the factors that affect these solvent properties, (2) to identify potential problem areas in the implementation of this approach, and (3) to suggest reasonable operating conditions.

Simple batch extractions were performed to assess the capacities of solvents for \( \text{CO}_2 \), \( \text{H}_2\text{S} \), and \( \text{NH}_3 \). The properties (aqueous solubility, phase separation, and regenerability) of the more likely solvents were studied in greater detail.

**EXPERIMENTAL METHODS**

**Reagents**

Table 1 lists the sources of the less conventional compounds used in this work. All compounds were used as received, with the exception of di-2-ethylhexyl phosphoric acid (D2EHPA) and octylphenyl phosphoric acid (OPAP). Mono-2-ethylhexyl phosphoric acid was removed from D2EHPA by the copper-salt-precipitation method described by McDowell, et al (1976). Titration of the purified product produced one endpoint of the strong acid type, indicating that the mono-2-ethylhexyl phosphoric acid had been largely removed from the D2EHPA. Mono-octylphenyl phosphoric acid was removed from OPAP by successive washings with sodium hydroxide solution, followed by a contacting with HCl and then water.
Analytical Methods

Concentrations of CO₂ and NH₃ in aqueous solutions were determined with specific-gas electrodes (Models 95-02 and 95-10, Orion Research Inc.) Concentrations of H₂S in aqueous solutions were determined with a specific-ion electrode (Orion Model 94-16) used in conjunction with an Orion Model 90-02 double-junction reference electrode.

Electrode responses were measured with an Orion Model 701A digital pH/mV meter with a five-channel electrode switch (Orion Model 605).

The pH of aqueous solutions was measured with either a Ag/AgCl pH electrode or a semi-micro combination pH electrode (Orion Model 91-03).

The concentration of solutes in organic phases was generally determined by mass balance. Occasionally, however, the concentration of ammonia in the organic phase was verified by back extraction of the ammonia into approximately 4 M H₂SO₄.

The concentration of water in the organic phase was determined by Karl Fischer titration.

Experimental Methods

Extractions: All extractions were performed in 125-mL separatory funnels. Normal procedure was to mix the two phases on a Labline Junior Orbit Shaker operated at about 250 RPM. In later work (NH₃ extractions) the aqueous phase (raffinate) was centrifuged after the extraction in an International Clinical Centrifuge (1200 RCM). In all cases concentration-based distribution coefficients ($K_c$) were calculated as:

$$K_c = \frac{C_F - C_R}{C_R} \left( \frac{W}{S} \right)$$ (1)
where \( C_F \) is the feed concentration (mol/L), \( C_R \) is the raffinate concentration (mol/L), \( W \) is the volume of aqueous phase, and \( S \) is the volume of solvent phase. This equation assumes total immiscibility of the phases.

**D2EHPA Solubility Measurements:** Raffinates generated in extractions using D2EHPA or OPAP extractant were twice centrifuged, and then the concentration of phosphorus in the aqueous phase was determined. The method used was a standard decomposition and precipitation method described by Pregl and Grant (1951). This analysis gave the mg P/mL solvent. This was converted to molarity or to ppm D2EHPA as follows:

\[
\text{ppm D2EHPA} = \text{mg P/mL} \times 1000 \times \frac{322}{30.9}
\]

Only purified D2EHPA or OPAP was used when making these measurements, since the high aqueous solubilities of the mono-esters would have distorted calculated values for D2EHPA or OPAP solubility. The solubility of D2EHPA in water as measured by this technique was 93 ppm, which compares well with the reported value of 100 ppm (Mobil Chemical Co., 1981).

**Solvent Regeneration Studies:** The ease of ammonia removal from solvents was determined by batch-stripping experiments. The NH\(_3\)-laden solvent was stripped at elevated temperatures, and the course of ammonia removal from the solvent was followed.

**Qualitative Studies:** In these studies the stripping medium was either vaporized solvent and nitrogen, or steam which was bubbled through the solvent.

**Quantitative Studies:** The apparatus used for these studies is shown in Figure 2. A relatively non-volatile diluent was used, and nitrogen was the sole stripping medium. After passing through the solvent, the NH\(_3\)-
containing nitrogen passed through a sulfuric acid solution which absorbed ammonia. The nitrogen then passed through a wet test meter. Measurement of the NH₃ concentration in the sulfuric acid solution after a given number of moles of nitrogen had passed through gave the number of moles of NH₃ stripped by that amount of nitrogen. This was converted to the partial pressure of NH₃ (P_{NH₃}) as follows:

\[
P_{NH₃} = \frac{\text{moles } NH₃}{\text{moles } NH₃ + \text{moles } N₂} \times \text{Pressure} \tag{3}
\]

It was not confirmed that this apparatus indeed provides equilibrium vapor.

**Extraction/Stripping Experiments:** These experiments were designed to compare the ease of CO₂ removal from an aqueous solution, in the presence of a solvent which extracted NH₃ and in the absence of such a solvent. The apparatus used was similar to that pictured in Figure 2, except that the experiments were conducted at room temperature, and an extra set of absorbers (for removal of CO₂ from the nitrogen stripping gas) was placed in series after the ammonia absorbers. The aqueous phase contained approximately 0.6 M NH₃ and CO₂. The solvent contained 0.48 M D2EHPA in either toluene, 50% (v/v) Alfol 10/toluene, or 0.53 M Adogen 364 in toluene. In one of the stripping cases no D2EHPA was present in toluene. In all cases the solvent-to-water volumetric phase ratio (S/W) was 2.5.

Further information on experimental procedures is available elsewhere (Mackenzie & King, 1984).
RESULTS AND DISCUSSION

Solvent Selection

Methyl isobutyl ketone (MIBK), 3 wt % TOPO in kerosene, ethyl acetate, dimethylaniline, 9% (v/v) Alamine 336 in kerosene and 9% (v/v) Adogen 283 in kerosene, at S/W = 1, and TBP, at S/W = 0.3, did not extract a measurable amount of CO_2 from an aqueous ammonium carbonate solution (initial concentration of CO_2 = 0.15 M).

No appreciable amount of H_2S was extracted from an ammonium sulfide solution (initial concentration of H_2S = 0.02 M) by 7.4% (v/v) Alamine 336 in kerosene or 7.4% (v/v) Adogen 283 in kerosene (S/W = 0.8). MIBK (S/W = 0.4) appeared to extract a small amount of H_2S, but the results were not reproducible.

No ammonia was extracted from the ammonium sulfide solution by MIBK. Likewise no NH_3 was extracted from an ammonium bicarbonate solution by toluene, 1-octanol, 50% (v/v) 1-decanol in toluene, 13% (w/w) nonylphenol in toluene, or 13% (w/w) 4-sec-butyl-2-(a-methylbenzyl) phenol in toluene (S/W = 5, initial concentration of ammonia = 0.58 M).

In light of these results it is apparent that stronger acids are required to remove NH_3 from an aqueous solution containing a weak acid such as CO_2 or H_2S. In particular, an acid which ionizes in the pH range of interest would offer the possibility of forming an ion pair with the ammonium cation. Since at the pH of the wastewater most of the NH_3 is in the NH_4^+ form, the driving force for ion pairing will be large. Extraction of NH_3 is preferable over that of acid gases because of the lower volatility of NH_3.

Liquid Cation Exchangers as Extractants for NH_3

Acidic extractants of the type of interest include carboxylic acids,
organic phosphoric acids and sulfonic acids. These acids are capable of extracting cations from aqueous solutions by an ion-exchanging mechanism and are known as liquid cation exchangers.

The basic mechanism of extraction of a monovalent cation by a liquid cation exchanger may be expressed as:

\[ M^+ + HA = M'A^- + H^+ \]  

(4)

where an overbar indicates organic-phase species. The organic acid, HA, ionizes at or near the aqueous/organic interface and exchanges its H\(^+\) for the cation, M\(^+\), forming an ion pair in the organic phase. This is a simplified expression which ignores possible dimerization of the extractant, complexing of the ion pair with additional acid molecules or diluent, and polymerization of the ion pair (Ashbrook, 1973).

The concentration-based distribution coefficient for NH\(_4^+\), K\(_{c, NH_4^+}\), is the ratio of the organic phase concentration of species containing ammonia to the aqueous phase concentration of NH\(_4^+\). It may be expressed in terms of the activity-based equilibrium constant for Equation 4, K\(_r\):

\[
K_{c, NH_4^+} = \frac{[NH_4^+]_o}{[NH_4^+]_a} = \frac{K_r [HA]^o M^a_\gamma A^o H^+ NH_4^+]_o}{(H^+)_a M^a_\gamma H^+ NH_4^+]_a}
\]

(5)

where square brackets and the superscript o denote organic-phase properties and parentheses and the superscript a denote aqueous-phase properties. \(\gamma\) is the activity coefficient.

From Equation 5 it is seen that K\(_{c, NH_4^+}\) increases with increasing pH. For the proposed process K\(_c\) for ammonia must be high in the pH range of interest, 7 to 9. At pH = 7 nearly all of the ammonia is in the ammonium form and K\(_c\) = K\(_{c, NH_4^+}\). Consequently K\(_{c, NH_4^+}\) must be large enough at a pH of about 7.

Liquid cation exchangers are usually quite viscous, so they are almost always used in diluted form. The solvent then is a solution of the organic acid (extractant) in an organic diluent.
Table 2 presents the results of the extraction of ammonium bicarbonate solutions containing 0.58 M ammonia with solvents containing either carboxylic acids or organic phosphoric acids, at S/W = 5. The values of pH were not determined but were estimated by pH paper to decrease from about 8 to about 5, going downward in the table. In light of this trend it is apparent that, as the acid strength of the extractant increases, NH₃ extractability increases. Only the last two extractants appear to exhibit sufficient Kᵅ values for effective extraction of ammonia.

D2EHPA is preferred over OPAP because it gives lower measured solubility losses. The raffinate from the OPAP extraction contained 0.009 M phosphorus, while that from the D2EHPA extraction contained 0.001 M phosphorus.

DNNSA was also considered as an extractant for ammonia. DNNSA is a stronger acid than D2EHPA. When 0.2 M D2EHPA (unpurified) in kerosene was contacted with an aqueous ammonium carbonate solution containing 0.17 M NH₃ at S/W = 1.25, the raffinate concentration was 0.036 M and the pH was about 5. When 0.18 M DNNSA was contacted with a similar feed at S/W = 1, the raffinate concentration was 0.0069 M and the pH was about 4. Phase-separation properties were slightly better with the DNNSA system, although both solvents showed some tendency to emulsify with the aqueous phase.

A qualitative assessment was made of the relative regenerabilities of D2EHPA and DNNSA. The solvents used in the regeneration studies were 0.19 M DNNSA in Norpar 12 containing 0.07 M NH₃, and 0.2 M D2EHPA in Norpar 12 containing 0.1 M NH₃. First water was boiled through the solvents at atmospheric pressure and at a cumulative water-to-solvent volumetric ratio of 1.0 for DNNSA and 0.5 for D2EHPA. For DNNSA no reduction in organic-phase ammonia concentration occurred, and no NH₃ was found in the aqueous distillate. For D2EHPA, a 32% reduction in organic-phase NH₃ concentration occurred, and 80% of the NH₃ stripped from the organic phase was collected in the aqueous distillate.
Solvent-regeneration experiments at 200°C used the diluent as part of the stripping medium. For DNNSA, 100 mL of solvent were held at 200°C for 2 hours with a nitrogen flow rate of 500 ml/min. For D2EHPA, 150 mL of solvent were held at 200°C for 2 hours with a nitrogen flow rate of 220 ml/min. The nitrogen was passed through a sulfuric acid solution to absorb NH₃ stripped from the solvent.

For the D2EHPA system, the NH₃ concentration in the organic phase was reduced to essentially zero, and 72% of the NH₃ lost from the organic phase was found in the sulfuric acid trap.

For the sulfonic acid system, a solid precipitated out of the solvent during the experiments, and the ammonia concentration of the solvent was reduced by at least 87%. No ammonia was found in the sulfuric acid trap. The solid was collected under various conditions, such as excluding light and/or oxygen, and was analyzed. There was no significant difference in the composition of the solids generated from NH₃-containing solvents. These solids had a molar ratio C:H:S of about 2:8:1, which is very different from that of DNNSA, 28:47:1. In addition the solids had a molar ratio of N to S between 0.8 and 0.9. These results indicate that a large portion of the alkyl part of the molecule was not incorporated into the solid decomposition product but that the ammonia was. Further, the ammonium salt of DNNSA appears to be preferentially decomposed.

No specific decomposition reaction was deduced, but it does appear that NH₃ cannot be stripped from a DNNSA-containing solvent without massive thermal decomposition of the extractant.

In summary, the results of solvent screenings indicated that of the extractants studied, D2EHPA was the preferred extractant for ammonia.
Screening of Diluents for D2EHPA

The effects of diluent choice on the solvent properties of D2EHPA were examined—particularly capacity to extract NH₃ ($K_c$), aqueous solubility of D2EHPA, and phase-separation properties.

As can be seen from Equation 5, any diluent which decreases the activity coefficient of the ion pair relative to that of the free acid will increase $K_{c, NH_4^+}$. This suggests that a diluent which solvates the ion pair better than it solvates the free acid will increase $K_{c, NH_4^+}$ (Blumberg and Gai, 1977). Conversely, a diluent which preferentially solvates the free acid over the ion pair will decrease $K_{c, NH_4^+}$.

Diluting an extractant will decrease its aqueous solubility losses since the reduction in concentration should decrease its activity. If the diluent can interact with the extractant and/or the ion pair, then solubility losses should also be less (Baes, 1962). For acidic extractants aqueous-phase solubility increases with increasing pH (Ashbrook, 1972).

All liquid cation exchangers possess some surface activity as a result of the presence of a hydrophilic group (the acid functionality) and a hydrophobic group (the hydrocarbon part). Conversion of the acid to the salt form generally, but not always, increases its surface activity (Cox and Flett, 1977). The salt form is usually more interfacially active than the acid because it is an ion pair and thus more hydrophilic. McDowell's (1977) observations suggest that the alkali salts of D2EHPA are more interfacially active than D2EHPA itself. A diluent which can interact with D2EHPA and especially the ion pair will reduce their activity. This can result in an increase in surface tension and a reduction in emulsification tendencies. The addition of a few percent of TBP or a higher alcohol to an organic phase to improve phase-separation tendencies is well known (Cox and Flett, 1977; Kunin and Winger, 1962).
In this work, phase-separation problems manifested themselves in the formation of white emulsions. These emulsions either encompassed all of the contents of the system or existed as a white emulsion zone at the interface of the two phases.

A comparison of diluents was made based on the results of batch extractions in which the feed contained approximately 0.58 M ammonia in an ammonium bicarbonate solution, S/W = 5, and the total concentration of D2EHPA in the organic phase was 0.2 M.

One-Diluent Systems

The use of Norpar 12 as a diluent resulted in high D2EHPA aqueous solubility losses (0.013 M). IBHK also produced comparatively high solubility losses (0.009 M). Toluene gave lower solubility losses (0.006 M). Phase-separation properties were slightly better in the latter case. These results suggest that the π electrons of the aromatic offer some solvation to the ion pair and probably also to D2EHPA.

Modifier-plus-Diluent Systems

Using a mixed diluent of some relatively inert diluent plus a modifier takes advantage of the chemical nature of a modifier which might be too viscous to be used alone. Several Lewis acids and bases were added as modifiers to toluene in a mixed diluent in order to assess their effects on D2EHPA solvent properties.

In these experiments the solvent contained 0.2 M D2EHPA in toluene plus various volume percents of the modifier. Some of the results for the effects on NH₃ extraction are presented as Figure 3. Results for aqueous extractant losses are presented as Figure 4. Specific observations of phase-settling properties are given elsewhere.
The weak Lewis bases hexyl ether and IBHK and the weak Lewis acid 1,1,2,2-tetrachloroethane had little effect on the capacity of D2EHPA for NH$_3$, greatly increased extractant losses, and gave rather poor phase-separation properties. Apparently toluene interacts with both the ion pair and free D2EHPA more strongly than do these compounds.

Strong Lewis bases did affect D2EHPA capacity for NH$_3$. D2EHPA capacity for NH$_3$ decreased as the Lewis base modifier was changed from TOPO to A364 to LA2, which is the order of increasing basicity. D2EHPA extractant losses to the aqueous phase were also reduced by the addition of these modifiers to toluene. This occurred despite a higher estimated pH of the raffinate from extractions using these modifiers. These effects indicate that the activity of free D2EHPA is reduced by these modifiers. This effect increases as the molar ratio of modifier to D2EHPA increases. Phase-separation properties also improved when these modifiers were added to the solvent. This is attributed to three possible effects—the reduction in D2EHPA activity, the reduction in concentration and hence activity of the ion pair, and the relatively high raffinate concentrations, resulting in higher ionic strengths.

The effects of adding alcohols, phenols and carboxylic acids as modifiers to toluene were also studied. The results shown in Figures 3 and 4 for 1-decanol are representative of the results for these compounds. These compounds increased D2EHPA capacity for NH$_3$, lowered aqueous extractant losses, and improved phase-separation properties. The effects were greater for the phenols and carboxylic acids than for the alcohols. The former are stronger acids than the latter. However compounds which are sterically hindered around the -OH group (BAMBP, neodecanoic acid) did not show these effects to as great an extent as the sterically unhindered compounds. These results suggest that these acid modifiers solvate the ion pair more than they solvate free
This solvation may occur via H-bonding with the phosphoryl group. This type of solvation may also make the ammonium cation of the ion pair more amenable to solvation by the basic functional groups of these modifiers, either the O in the -OH group or the carbonyl of the acids.

From these studies two types of useful modifier behavior were discerned. First are the modifiers which increase $K_c$ and decrease extractant losses, mostly through solvation of the ion pair. Second are the modifiers which decrease $K_c$ and decrease extractant losses mostly through solvation of free D2EHPA. The properties of solvents representing these two classes were examined in more detail. Specifically the properties of D2EHPA in the following diluents were studied: (1) 50% (v/v) decanol in toluene or Norpar 12, (2) Adogen 364 in toluene or Norpar 12, and, for comparison, (3) toluene or Norpar 12.

**Characterization of D2EHPA-containing Solvents**

$K_{c, NH_4^+}$. Distribution coefficients were measured as a function of aqueous-phase pH at three D2EHPA concentrations (0.48 M, 0.37 M, and 0.25 M) in each of the above-mentioned diluents. The feed for these extractions was an ammonium hydroxide/ammonium phosphate solution. The concentration of the ammonium/D2EHPA ion pair in the organic phase was varied by changing the concentration of ammonium hydroxide in the feed. The results are presented in Figures 5 and 6 as $(pH - \log K_{c, NH_4^+})$ versus stoichiometry ($s$), which is the concentration of the ammonium/D2EHPA ion pair in the organic phase divided by the total concentration of D2EHPA ($[HA]_0$).

From Equation 5, at constant $[HA]$, $(pH - \log K_{c, NH_4^+})$ is proportional to $\log (\gamma_{NH_4^+_A}^o/\gamma_{HA}^o)$, if aqueous phase activity coefficients are neglected. At constant $s$ and total D2EHPA concentration, $[HA]$ is approximately constant. Therefore as the value of $(pH - \log K_{c, NH_4^+})$ decreases, $\gamma_{NH_4^+_A}^o/\gamma_{HA}^o$ decreases,
indicating preferential solvation of the ion pair over D2EHPA. This value is lowest in the alcohol diluent and highest in the amine diluent. This again indicates that the alcohol preferentially solvates the ion pair and that the amine preferentially solvates free D2EHPA. This latter effect increases as the molar ratio of amine to D2EHPA increases.

\[ K_{c,\text{NH}_4^+} \] at a given pH and total D2EHPA concentration decreases as stoichiometry increases, reflecting the decrease in the concentration of free D2EHPA. Also, at a given pH and stoichiometry, \( K_{c,\text{NH}_4^+} \) increases as the total concentration of D2EHPA increases, reflecting the increase in concentration of free D2EHPA.

No attempt was made to determine the composition of the species present in the organic phase. Instead a simplified approach suggested by McDowell was pursued. Since the composition of the complexes in the organic phase can depend on stoichiometry McDowell suggests plotting \( \log K_{c,\text{NH}_4^+} - \text{pH} \) versus \( \log [HA]_o \) at constant stoichiometry. The slope of these plots (n) should be a reflection of the degree of complexation of the ion pair by additional D2EHPA. Sample plots are shown in Figures 7 and 8. Tables 3 and 4 give the values of the slopes and intercepts as calculated by a least squares fit to the data. Additional results are also given for cases in which only two data points were available.

For the toluene diluent values of n are higher at low stoichiometry. This is consistent with McDowell's work on the extraction of alkali metals into D2EHPA in benzene and suggests that additional complexation of the ion pair by D2EHPA occurs at low stoichiometry, when additional D2EHPA is available for such solvation.

For the amine diluent a more mechanistic model was pursued. The interaction of the amine (B) with D2EHPA (HA) to form an amine/D2EHPA complex was
written as:

\[ B: + HA \rightleftharpoons B:HA \quad (6) \]

The equilibrium constant of this reaction, \( K_{B:HA} \), was calculated. At a given stoichiometry the concentration of D2EHPA not associated with amine or ammonium was calculated by multiplying the ratio of \( K_{c,\text{NH}_4}^+ \) value for the amine diluent to that for the toluene diluent, at the same pH, by the concentration of D2EHPA not associated with ammonium. Mass balances for the amine and for D2EHPA provided the other values needed to calculate \( K_{B:HA} \). For cases in which the (amine plus ammonium)-to-D2EHPA molar ratio was greater than one, the calculated values of \( K_{B:HA} \) were all about 2000 liter/mole. For cases in which this ratio was less than one it was necessary to include an additional equilibrium between the amine/D2EHPA complex and additional D2EHPA (Mackenzie and King, 1984).

**Phase-separation properties.** Several factors can affect the phase-separation properties of the systems under study. In general the alcohol diluent systems gave better phase-separation properties than either the toluene diluent or the amine-containing diluent. Other factors which appeared to cause phase-separation problems were high D2EHPA concentration, high concentration of the ammonium/D2EHPA ion pair, low raffinate concentrations, and low S/W and high stoichiometry, especially for the toluene diluent.

**Aqueous-phase extractant losses.** Table 5 presents results for measured concentration of phosphorus in the aqueous raffinate after an extraction. All of the measured phosphorus was assumed to be D2EHPA, since purified D2EHPA was used in these studies. Further it was assumed that all of the D2EHPA was ionized since the pH values are significantly greater than the \( \text{pK}_a \) of D2EHPA, which is about 3.
From the first two entries in Table 5 it is seen that at the same pH and approximately the same concentration of free D2EHPA the alcohol diluent gave lower D2EHPA solubility losses than the toluene diluent, indicating that it solvates D2EHPA better than toluene. A similar though less strong conclusion can be drawn from the data in lines 4 and 5. The amine modifier solvates D2EHPA very strongly, as evidenced by the low D2EHPA solubility losses it produced despite the higher pH (lines 3 and 6). As the amine-to-D2EHPA molar ratio increases, the effect of this solvation increases, and solubility losses at a given pH become very low.

Table 6 gives results for measured concentrations of phosphorus in raffinates after back-extraction of the raffinates with fresh (NH₃-free) organic phase. Again the alcohol appears to solvate D2EHPA better than toluene. Also, as the molar ratio of amine to D2EHPA increases solubility losses at a given pH become lower.

Water Coextraction. In general, the moles of water coextracted per mole of ammonium/D2EHPA ion pair increased as stoichiometry increased, as can be seen in Table 7. The amount of water coextracted by the solvent alone leads to artificially high values of this ratio at low stoichiometry. However, in a general sense, it can be stated that at a stoichiometry below 0.5 the lowest water coextraction occurred into the toluene-diluent systems. Above this stoichiometry water coextraction was lowest into the alcohol-diluent systems. At high stoichiometry water coextraction was greatest into the toluene-diluent systems.

If the amount of water coextracted by the diluent alone is subtracted from the total measured water concentrations, the moles of water coextracted per mole ammonium/D2EHPA ion pair were less for the alcohol diluent than for the other diluents, suggesting that the alcohol replaces part
of the water as the solvating medium for the ammonium/D2EHPA ion pair, making it more organophilic and thus more extractable.

Removing the ammonia from the D2EHPA-containing solvent resulted in a reduction in the amount of water in the solvent. This indicates that a large portion of the water coextracted into the organic phase is associated with the ammonium/D2EHPA ion pair.

**Solvent Regeneration Properties.** Ammonia is released from the solvent when the ammonium/D2EHPA ion pair breaks apart. This may be viewed by the following reaction:

\[ \text{NH}_4^+ \text{A}^- \rightarrow \text{HA} + \text{NH}_3^+ \]  

(7)

The partial pressure of ammonia above the solvent, \( P_{\text{NH}_3} \), may be expressed in terms of the \( \text{NH}_3 \) concentration in the organic phase and a Henry's law constant, \( H \). Combining this with an equilibrium constant for the above reaction (\( K' \)) yields:

\[ P_{\text{NH}_3} = \frac{\text{NH}_4^+ \text{A}^- \gamma_{\text{NH}_3^+}}{K' \gamma_{\text{HA}} \gamma_{\text{NH}_3}} \]  

(8)

High \( P_{\text{NH}_3} \) will result from high concentration of the ammonium/D2EHPA ion pair, from low concentration of free D2EHPA, and in solvents in which the ammonium/D2EHPA ion pair is not well solvated (high \( \gamma \) for the ammonium/D2EHPA ion pair) or free D2EHPA is well solvated (low \( \gamma \) for D2EHPA). The results as \( P_{\text{NH}_3} \) versus concentration of the ammonium/D2EHPA ion pair for the different solvents are presented in Figures 9 and 10 and can be interpreted in terms of Equation 8.

**Figure 9** summarizes the effects of temperature and diluent on \( P_{\text{NH}_3} \). As expected, for a given diluent \( P_{\text{NH}_3} \) increases with increasing temperature. At
a given temperature $P_{NH_3}$ was greater for the inert diluent than for the alcohol diluent. The lower $P_{NH_3}$ values for the alcohol diluent are apparently due to the solvation of the ammonium/D2EHPA ion pair by the alcohol.

In Figure 10 the effect of increasing the total concentration of D2EHPA is seen. At the same concentration of ammonium/D2EHPA ion pair, $P_{NH_3}$ is less for the more concentrated diluent due to the higher concentration of free D2EHPA.

The effect of adding Lewis bases to the solvent is to increase $P_{NH_3}$, as seen in Figure 10. These compounds lower the activity of free D2EHPA. Adding A364 produced a greater effect than adding the weaker base TOPO. The effect increased as the molar ratio of amine to D2EHPA increased.

The values of $K$ in Equation 8 were calculated for the alcohol and Norpar 12 diluents. In these calculations $[HA]$ was set equal to the total concentration of D2EHPA minus the concentration of the ammonium/D2EHPA ion pair. For the alcohol diluent values of $K$ were fairly constant between the low- and high-concentration solvents and in general decreased some with decreases in stoichiometry, indicating a reduction in the activity coefficient of the ammonium/D2EHPA ion pair. At 127°C the average $K$ value in the stoichiometry range 0.75 to 0.5 was $8.6 \times 10^{-3}$ atm. For the range 0.5 to 0.25 it was $7 \times 10^{-3}$ atm, and below 0.25 it was $3.1 \times 10^{-3}$ atm. At 143°C the first two values were $1.7 \times 10^{-2}$ atm and $1.4 \times 10^{-2}$ atm, respectively. This model indicates that for the alcohol diluent $P_{NH_3}$ is determined solely by stoichiometry.

For the Norpar 12 diluent, $K$ was not constant between the low- and high-concentration solvents. Allowing for additional complexation by D2EHPA gave more nearly constant $K$ values. Thus for the inert diluent $P_{NH_3}$ was modelled as:

$$P_{NH_3} = \frac{K'' [NH_4^+ A^-]}{[HA]^2}$$

(9)
As in the development of the liquid-liquid extraction equilibrium models, this extra solvent dependency is intended only to indicate additional complexation of the ion pair by D2EHPA and does not confirm the presence of a particular species in the organic phase. At 127°C in the stoichiometry range 0.5 to 0.25, the average $K''$ was $4.9 \times 10^{-3}$ atm M, and below 0.25 it was $3.4 \times 10^{-3}$ atm M. At 143°C these values were $1.3 \times 10^{-2}$ atm M and $1.1 \times 10^{-2}$ atm M, respectively.

The data for the amine-containing diluents were found to be independent of the concentration of free D2EHPA.

Some insight into the effect of temperature on $K_c$ can be discerned by consideration of the ratios of $P_{NH_3}$ values in different diluents. At a given concentration of the ammonium/D2EHPA ion pair, the ratio of $P_{NH_3}$ values in two different solvents is inversely proportional to the ratio of their $K_c$ values. This ratio can be compared to the ratio of $K_c$ values at room temperature. These values were estimated by calculating $K_{c,NH_4^+}$ values from Figures 5 and 6 at pH equal to 9.25. At this pH $K_c$ is equal to $K_{c,NH_4^+}$.

The effect of raising temperature is to bring $K_{c,NH_3}$ values for the different diluents closer together. The ratio of the $P_{NH_3}$ value at 127°C for the amine diluent to that for the Norpar 12 diluent at an amine-to-D2EHPA molar ratio of 1:2 is about 4, while the ratio of $K_c$ values at 25°C (toluene to amine diluent) is on the order of 100. At an amine-to-D2EHPA molar ratio of 1:1 these values are about 5 and 300, respectively. This suggests that the amine/D2EHPA complex is weaker at higher temperatures, which would be expected.

A similar effect is seen with the alcohol diluent. The ratio the of $P_{NH_3}$ value at 127°C for the Norpar 12 diluent to that for the alcohol diluent is
about 3. The ratio of $K_c$ values at 25°C (alcohol to toluene diluent) is about 6. This indicates that the alcohol is less effective at solvating the ammonium/D2EHPA ion pair at higher temperatures than it is at lower temperatures.

Comparison of Extraction/Stripping with Stripping Alone

The results for CO$_2$ removal from aqueous solutions are presented in Figure 11. The data are plotted as the fraction of CO$_2$ left in the solution as a function of the cubic feet of nitrogen passed through 50 mL of aqueous solution.

The data indicate that CO$_2$ is much more readily stripped from solution in the presence of a solvent containing D2EHPA. Specifically CO$_2$ removal is highest when the diluent for D2EHPA is an alcohol, followed by toluene, and then the amine-containing diluent. This is the order of decreasing $K_{c,NH_4^+}$ values. Thus the solvent which is most effective in extracting ammonia from the aqueous solution results in highest CO$_2$ volatility. This is a result of the lower aqueous-phase pH, due to removal of the base, NH$_3$.

For the stripping in the absence of a solvent, at the end of the experiment 20% of the ammonia initially present in the aqueous phase had been stripped from the solution along with the CO$_2$. For the cases with a D2EHPA-containing solvent present, the amount of the ammonia initially present in the aqueous phase and stripped with the CO$_2$ ranged from 0.06% (alcohol diluent) to 1.5% (amine diluent).

These experiments demonstrate that the combination of stripping and solvent extraction serves to enhance CO$_2$ volatility and reduce NH$_3$ volatility, thereby making the CO$_2$ easier to strip and enabling isolation of the ammonia from the CO$_2$. 
Design Considerations

Some preliminary calculations were performed to estimate the costs for the proposed extraction/stripping process (Mackenzie and King, 1984). The costs considered were steam costs for the acid-gas stripper, steam costs for the solvent regeneration column and the cost for replenishing D2EHPA lost through aqueous solubility. The latter two costs appear to be dominant.

With D2EHPA-containing solvents, the upper limit on regeneration temperature appears to be about 130 °C. Higher temperatures cause significant thermal degradation of D2EHPA (Mackenzie and King, 1984). With this temperature and a diluent giving a pressure of 0.4 atm, the costs for regenerating the solvent ranged from $2.30/1000 gal water (inert diluent) to $9.40/1000 gal water (alcohol diluent). In these cases the solvent is only partially regenerated and then recycled. Costs for replacing D2EHPA ranged from $4/1000 gal (alcohol diluent) to $19/1000 gal (amine diluent), at a D2EHPA cost of $2.60/lb. These costs are higher than ones that have been cited for the Phosam-W process.

Energy requirements for solvent regeneration could be reduced by using a more thermally stable solvent, so that the regeneration could be carried out at higher temperatures. Alternatively the use of a weaker extractant could be considered. This would have the potential advantage of the complexation being more readily reversible and thus requiring less energy or a lower temperature for regeneration. However this would be at the expense of higher S/W in the extraction part of the process and/or less effective ammonia removal.

Solvent replenishment costs could be reduced if D2EHPA could be recovered from the aqueous phase, perhaps by adsorption or acidification. Alternatively a less-water-soluble extractant could be considered.
Acknowledgement

This work was supported by the Assistant Secretary for the Environment, Office of Environmental Compliance and Overview, Division of Environmental and Safety Engineering, Environmental Control Technology Branch, U. S. Department of Energy and by the Fossil Energy Division through the Morgantown Energy Technology Center, under Contract No. DE-AC03-76SF00098.

Support was also received from a Genevieve McEnerny Fellowship and a Domestic Mining and Mineral and Mineral Fuel Conservation Fellowship.

REFERENCES


Mobil Chemical Company, Industrial Chemicals Group, Phosphorus Division, Richmond, VA, 1981, Bulletin #081201.


TABLE 1. SOURCES AND DESCRIPTION OF CHEMICALS USED

<table>
<thead>
<tr>
<th>COMPOUND</th>
<th>SUPPLIER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adogen 283</td>
<td>Ashland Chemicals</td>
<td>2° amine, C_{13} branched</td>
</tr>
<tr>
<td>Adogen 364</td>
<td>Ashland Chemicals</td>
<td>3° amine, C_{8}-C_{10} straight-chain</td>
</tr>
<tr>
<td>Alamine 336</td>
<td>General Mills</td>
<td>3° amine, C_{8}-C_{10} straight-chain</td>
</tr>
<tr>
<td>Alfol 10</td>
<td>Conoco Chemical</td>
<td>1-decanol</td>
</tr>
<tr>
<td>Amberlite LA-2</td>
<td>Rohm and Haas</td>
<td>2° amine, highly branched</td>
</tr>
<tr>
<td>BAMBP</td>
<td>Frinton Laboratories</td>
<td>4-sec-butyl-2-(a-methyl benzyl) phenol</td>
</tr>
<tr>
<td>Di-2-ethyl hexyl phosphoric acid (D2EHPA)</td>
<td>Mobil Chemical Co.</td>
<td>technical grade</td>
</tr>
<tr>
<td>Dinonyl naphthalene sulfonic acid (DNNSA)</td>
<td>King Industries</td>
<td>DN-052:50% in Norpar 12</td>
</tr>
<tr>
<td>Isobutyl-heptyl ketone (IBHK)</td>
<td>Union Carbide</td>
<td>DN-040:40% in heptane</td>
</tr>
<tr>
<td>Isodecyl alcohol</td>
<td>USS Chemicals</td>
<td>2-methyl-4-decanone, technical grade</td>
</tr>
<tr>
<td>Neodecanoic acid</td>
<td>Exxon Chemicals</td>
<td>branched-chain primary aliphatic alcohol</td>
</tr>
<tr>
<td>Nonyl phenol (NP)</td>
<td>ICN Pharmaceuticals</td>
<td>branched, technical grade</td>
</tr>
<tr>
<td>Norpar 12</td>
<td>King Industries</td>
<td>n-C_{10}-C_{13} paraffins</td>
</tr>
<tr>
<td>Octyl phenyl acid phosphate (OPAP)</td>
<td>Mobil Chemical Co.</td>
<td>50% mixture of mono- and di-esters</td>
</tr>
<tr>
<td>Tributyl phosphate (TBP)</td>
<td>Mobil Chemical Co.</td>
<td>technical grade</td>
</tr>
<tr>
<td>Tri-n-octyl phosphine oxide (TOPO)</td>
<td>American Cyanamid</td>
<td>technical grade</td>
</tr>
</tbody>
</table>
### TABLE 2. COMPARISON OF LIQUID CATION EXCHANGERS AS EXTRACTANTS FOR AMMONIA.

Diluent: 50% decanol in toluene. S/W (v/v) = 5.

<table>
<thead>
<tr>
<th>Extractant</th>
<th>[Extractant] (mol/L)</th>
<th>(N)(a) (mol/L)</th>
<th>K_c</th>
<th>pK_a</th>
</tr>
</thead>
<tbody>
<tr>
<td>neodecanoic acid</td>
<td>0.27</td>
<td>0.47</td>
<td>0.034</td>
<td>7(b)</td>
</tr>
<tr>
<td>decanoic acid</td>
<td>0.27</td>
<td>0.35</td>
<td>0.12</td>
<td>5</td>
</tr>
<tr>
<td>D2EHPA</td>
<td>0.21</td>
<td>0.017</td>
<td>6.1</td>
<td>3(c)</td>
</tr>
<tr>
<td>OPAP</td>
<td>0.18</td>
<td>0.012</td>
<td>7.5</td>
<td>&lt;3</td>
</tr>
</tbody>
</table>

(a): Measured total concentration of ammonia in raffinate.


(c) Kunin and Winger, 1962.
<table>
<thead>
<tr>
<th>s(b)</th>
<th>n</th>
<th>-I</th>
<th>correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>3.36</td>
<td>3.75</td>
<td>0.985</td>
</tr>
<tr>
<td>0.26</td>
<td>2.18</td>
<td>4.46</td>
<td>-</td>
</tr>
<tr>
<td>0.53</td>
<td>1.29</td>
<td>5.09</td>
<td>1</td>
</tr>
<tr>
<td>0.78</td>
<td>1.24</td>
<td>5.31</td>
<td>0.96</td>
</tr>
<tr>
<td>0.94</td>
<td>0.64</td>
<td>5.79</td>
<td>-</td>
</tr>
</tbody>
</table>

(a): Parameters defined in Equation: $\log K_{c,\text{NH}_4^+} - \text{pH} = n \log ([\text{D2EHPA}]_o) + I$

(b): Stoichiometry = $[\text{NH}_4^+\text{A}^-]/[\text{D2EHPA}]_o$
<table>
<thead>
<tr>
<th>s(b)</th>
<th>n</th>
<th>-I</th>
<th>correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>1.5</td>
<td>3.78</td>
<td>0.96</td>
</tr>
<tr>
<td>0.27</td>
<td>1.4</td>
<td>3.86</td>
<td>-</td>
</tr>
<tr>
<td>0.54</td>
<td>1.14</td>
<td>4.25</td>
<td>0.98</td>
</tr>
<tr>
<td>0.79</td>
<td>1.21</td>
<td>4.56</td>
<td>0.92</td>
</tr>
<tr>
<td>0.92</td>
<td>1.4</td>
<td>4.84</td>
<td>0.97</td>
</tr>
</tbody>
</table>

(a): Parameters defined in Equation: \( \log K_{c,\text{NH}_4^+ - \text{pH}} = n \log (\text{D2EHPA})_0 + I \)

(b): Stoichiometry = \( [\text{NH}_4^+\text{A}^-]/[\text{D2EHPA}]_0 \)
<table>
<thead>
<tr>
<th>Diluent</th>
<th>[D2EHPA] (mol/L)</th>
<th>pH</th>
<th>p(a) (mol/L)</th>
<th>[NH₄⁺A⁻] (mol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% (v/v) 1-decanol/toluene</td>
<td>0.2</td>
<td>6(b)</td>
<td>0.0009</td>
<td>0.1</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.2</td>
<td>6(b)</td>
<td>0.0058</td>
<td>0.1</td>
</tr>
<tr>
<td>0.08 M A364/toluene</td>
<td>0.2</td>
<td>7.2(b)</td>
<td>0.0023</td>
<td>0.08</td>
</tr>
<tr>
<td>50% (v/v) Alfol 10/toluene</td>
<td>0.48</td>
<td>6.2</td>
<td>0.004</td>
<td>0.25</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.48</td>
<td>6.57</td>
<td>0.0125</td>
<td>0.23</td>
</tr>
<tr>
<td>0.52 M A364/toluene</td>
<td>0.48</td>
<td>8.7</td>
<td>0.006</td>
<td>0.21</td>
</tr>
</tbody>
</table>

(a): Measured aqueous-phase phosphorus concentration  
(b): Estimated from liquid-liquid equilibrium data
<table>
<thead>
<tr>
<th>Diluent</th>
<th>[D2EHPA] (mol/L)</th>
<th>(N)(^{(a)}) (mol/L)</th>
<th>pH (mol/L)</th>
<th>p(^{(b)}) (mol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% Alfol/toluene</td>
<td>0.48</td>
<td>0.004(^{(c)})</td>
<td>6(^{(c)})</td>
<td>0.00055</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.48</td>
<td>0.005</td>
<td>4.6</td>
<td>0.0015</td>
</tr>
<tr>
<td>0.52 M A364/toluene</td>
<td>0.48</td>
<td>0.02</td>
<td>8</td>
<td>0.003</td>
</tr>
<tr>
<td>0.52 M A364/toluene</td>
<td>0.45</td>
<td>0.0086</td>
<td>6(^{(d)})</td>
<td>0.0028</td>
</tr>
</tbody>
</table>

(a): Measured total concentration of ammonia in raffinate
(b): Measured concentration of phosphorus in raffinate
(c): Values not stable
(d): Estimated from liquid-liquid equilibrium data
### TABLE 7: WATER COEXTRACTION

<table>
<thead>
<tr>
<th>[D2EHPA] (mol/L)</th>
<th>[NH₄⁺A⁻] (mol/L)</th>
<th>[H₂O] (mol/L)</th>
<th>[H₂O] (mol/L)</th>
<th>[H₂O] (mol/L)</th>
<th>[H₂O] (mol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.035</td>
<td>0.08</td>
<td>0.60</td>
<td>0.14</td>
<td>0.58(b)</td>
</tr>
<tr>
<td>0.25</td>
<td>0.23</td>
<td>2.04</td>
<td>1.53</td>
<td>1.9</td>
<td>1.6(c)</td>
</tr>
<tr>
<td>0.48</td>
<td>0.07</td>
<td>0.12</td>
<td>0.70</td>
<td>0.41</td>
<td>0.51(d)</td>
</tr>
<tr>
<td>0.48</td>
<td>0.46</td>
<td>5.06</td>
<td>2.84</td>
<td>4.2</td>
<td>3.1(e)</td>
</tr>
</tbody>
</table>

(a): Measured concentration of water in organic phase
(b): [NH₄⁺A⁻] = 0.026 mol/L
(c): [NH₄⁺A⁻] = 0.203 mol/L
(d): [NH₄⁺A⁻] = 0.051 mol/L
(e): [NH₄⁺A⁻] = 0.37 mol/L
Figure 1. Combined Solvent Extraction and Stripping.
Figure 2. Stripping Apparatus for Solvent-Regeneration Studies.
Figure 3: Effect Upon D2EHPA Extraction of Ammonia From Adding Various Lewis Acids and Bases as Modifiers to a Toluene Diluent. Aqueous feed: 0.58 M NH₄HCO₃; 0.2 M D2EHPA in organic phase; S/W (v/v) = 5. Modifiers: TOPO = tri-n-octyl phosphine oxide; TCE = 1,1,2,2-Tetrachloroethane; HE = Hexyl ether; IBHK = Isobutyl-heptyl ketone; nC₁₀-OH = 1-Decanol; LA2 = Amberlite LA-2; A364 = Adogen 364.
Figure 4. Effect upon D2EHPA Aqueous Solubility Losses from Adding Various Lewis Acids and Bases as Modifiers to a Toluene Diluent. Legend: See Figure 3.
Figure 5. Effect of Stoichiometry on $K_{c,NH_4^+}$ for Toluene + Alcohol-Containing Diluents.
Figure 6. Effect of Stoichiometry on $K_{c,NH_4^+}$ for Amine-Containing Diluents.
Figure 7. Effect of D2EHPA Concentration on $K_{c, NH_4^+}$ for Toluene Diluent.
Figure 8. Effect of D2EHPA Concentration on $K_{c, NH_4^+}$ for Alcohol-Containing Diluents.
Figure 9. Effects of Temperature and Diluent on Solvent-Regeneration Properties.
Figure 10. Effects of D2EHPA Concentration and Diluent Modifiers on Solvent-Regeneration Properties.
Figure 11. Comparison of Ease of CO₂ Removal by Stripping with that by Extraction/Stripping.

Feed = 0.58 M NH₄HCO₃; S/W = 2.5; [HA] = 0.48 M.
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.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.