

## Conductivity of electrolytes for rechargeable lithium batteries

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### Abstract

We report the conductivity of 150 non-aqueous electrolytes for rechargeable Li batteries between  $-60$  and  $80$  °C. A wide range of solvents including esters, ethers, aromatics, chlorinated solvents, etc., and mixtures thereof, were studied. Results for five electrolyte salts which have some promise for rechargeable Li cells are presented. The data are organized alphabetically by solvent in Tables for each salt. These Tables should prove to be useful for workers in the Li battery field. We discuss several of the trends in the data and show the importance of solvent viscosity in determining electrolyte conductivity.

### Introduction

The composition of the non-aqueous organic electrolyte for secondary Li batteries plays a major role in determining cycle life, cell performance, operating temperature range, and storage temperature range. Our recent work [1, 2] shows that the choice of electrolyte also strongly affects the response of cycled cells to thermal and electrical abuse. The selection and optimization of an electrolyte for practical cells depends on a number of factors, one of which is the electrolyte conductivity.

There have been numerous studies and reviews regarding the conductivity and properties of non-aqueous electrolytes (e.g., refs 3–7). There have been many others regarding the performance of test cells using various electrolyte and cathode combinations (e.g., refs 2, 8, 9). From these works a variety of standard approaches to the formulation of high conductivity electrolytes for secondary Li cells has evolved. Quite commonly, high dielectric constant solvents such as ethylene carbonate (EC) or propylene carbonate (PC) are mixed with low-viscosity, low-dielectric-constant solvents such as 2-methyl-tetrahydrofuran (2-MeTHF) to obtain improved conductivity [8]. Ternary

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solvent blends are sometimes used to increase low temperature performance even further [9] Hydrocarbon compounds such as decalin have been added in small amounts to improve Li morphology [10] However, there is not yet a complete understanding of multi-component electrolyte systems to allow, *a priori*, the selection of an optimum electrolyte for a particular secondary Li cell

The choice of Li salt is, apparently, also complex Our work has shown that  $\text{LiAsF}_6$ ,  $\text{LiCF}_3\text{SO}_3$  and  $\text{LiN}(\text{CF}_3\text{SO}_2)_2$  are the most useful salts in  $\text{Li}/\text{MoS}_2$  and in  $\text{Li}/\text{MnO}_2$  secondary cells Other salts such as  $\text{LiBF}_4$  and  $\text{LiPF}_6$  show some promise Less common salts (e.g., ref 11) have also been proposed and tested  $\text{LiClO}_4$  has been almost unanimously rejected by the battery community for secondary cells because of safety problems

Here we present the results of electrolyte conductivity measurements on a wide range of pure and multi-solvent electrolytes using the salts  $\text{LiAsF}_6$ ,  $\text{LiN}(\text{CF}_3\text{SO}_2)_2$ ,  $\text{LiCF}_3\text{SO}_3$ ,  $\text{LiBF}_4$ , and  $\text{LiPF}_6$  The presentation of the data in alphabetized tabular form is intended to provide a useful compilation for workers in the field We present graphs of some of the data to show trends

We have studied three solvent mixtures in greatest detail, as is reflected in the Tables These are EC/PC, 2-MeTHF/EC/PC and sulfolane/triglyme The first solvent mixture is that found in the commercial  $\text{Li}/\text{MoS}_2$  MOLICEL<sup>®</sup> and in our prototype  $\text{Li}/\text{MnO}_2$  MOLICEL<sup>2</sup> This is a low vapour pressure, high flash point solvent system suited to low cost manufacturing and gives acceptable safety performance in "AA" size cells 2-MeTHF/EC/PC mixtures give increased low temperature performance over EC/PC mixtures and give good cycle life However, this electrolyte uses 2-MeTHF, which has a low flash point and a high vapour pressure Cycled cells containing 2-MeTHF have been found by us to be less safe than those with only EC/PC solvents 2-MeTHF/EC/PC electrolytes may be suitable for cells targeted for military applications Finally, sulfolane/triglyme-based electrolytes give acceptable cycle life in  $\text{Li}/\text{MnO}_2$  cells and are not ester based

Aromatic compounds such as benzene, toluene, cumene, etc., and halogenated solvents similar to methylene chloride have also been investigated as additives The motivation for this work was

(i) many aromatic and halogenated solvents have low viscosity, but do not dissolve substantial amounts of Li salts in pure form Thus, simple 'viscosity reducers' can be added to high dielectric solvents to increase conductivity,

(ii) aromatics which contain only H and C atoms react only weakly with Li [10] We felt that safer cells could be made through the addition of substantial amounts of aromatics to cell electrolytes, as is suggested in the patent literature [12],

(iii) many chlorinated hydrocarbons have no flash point We thought that adding these compounds could lead to safer cells

Many of the aromatic- and halogen-containing electrolytes tested here did show acceptable cycle life in  $\text{Li}/\text{MnO}_2$  cells, but the safety benefits we had hoped for did not appear This work will be the subject of a future publication

## Experimental

$\text{LiAsF}_6$  was purchased from Lithium Corporation of America and used as received.  $\text{LiN}(\text{CF}_3\text{SO}_2)_2$  and  $\text{LiCF}_3\text{SO}_3$  were purchased from 3M Corporation.  $\text{LiPF}_6$  and  $\text{LiBF}_4$  were purchased from Aldrich Chemical Co. The latter four salts were all vacuum dried at elevated temperature to remove moisture. Figure 1 shows TGA experiments carried out on each salt under He gas at a heating rate of  $50^\circ\text{C min}^{-1}$ . Each of the salts decomposes to  $\text{LiF}$  (verified by X-ray diffraction of the product) and gaseous products. Table 1 compares the weight fraction of  $\text{LiF}$  expected, based on the salt molecular weight, with that measured from the TGA curves at  $600^\circ\text{C}$ . Apart from  $\text{LiPF}_6$ , the agreement between experiment and theory is excellent. The vacuum drying temperatures were picked to be well below the salt decomposition temperatures. The drying temperatures for  $\text{LiCF}_3\text{SO}_3$ ,  $\text{LiBF}_4$ ,  $\text{LiPF}_6$ , and  $\text{LiN}(\text{CF}_3\text{SO}_2)_2$  were  $150$ ,  $115$ ,  $80$ , and  $120^\circ\text{C}$ , respectively. All salts were dried for 24 h.

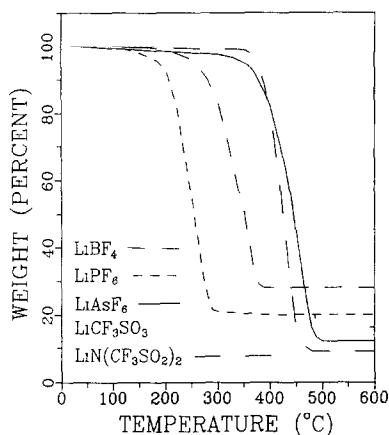


Fig 1 Thermogravimetric analysis of Li salts under helium gas. The sample size was approximately 30 mg, the He flow rate was  $50\text{ cm}^3\text{ min}^{-1}$  and the temperature was increased at  $50^\circ\text{C min}^{-1}$ .

TABLE 1

Weight percent of  $\text{LiF}$  compared with original salt mass in thermal decomposition of Li salts by TGA

Salt	Final weight expected (%)	Final weight observed (%)
$\text{LiPF}_6$	17.1	$20 \pm 1$
$\text{LiBF}_4$	27.7	$28 \pm 1$
$\text{LiAsF}_6$	13.2	$12 \pm 1$
$\text{LiCF}_3\text{SO}_3$	16.3	$16 \pm 1$
$\text{LiN}(\text{CF}_3\text{SO}_2)_2$	9.0	$9 \pm 1$

It is possible that at 80 °C, however, where  $\text{LiPF}_6$  was vacuum dried, that some decomposition to  $\text{LiF}$  had occurred during drying, leading to the slightly higher residual mass (Table 1) We did not think this would affect conductivity measurements significantly so the  $\text{LiPF}_6$  was still used

The solvents studied are listed in Table 2 The short code referring to each solvent in the rest of the Tables is also given The physical property data have been collected from various literature Tables

PC and EC were obtained from Texaco Sulfolane was obtained from Phillips 66 and triglyme from the Ferro Corporation These four solvents were purified by fractional distillation After distillation, total impurity contents were less than 100 ppm as measured by GC/MS THF, 2-MeTHF, DME and ethylmonoglyme were obtained from Aldrich Chemical Corp and were purified by distillation from lithium benzophenone All other solvents were obtained from Aldrich Chemical Corp and were not distilled Moisture contents of all solvents were reduced when necessary by drying over 4A molecular sieves

Electrolytes were mixed by slow additions of salt, while stirring to avoid excessive heating due to the heat of solvation Moisture measurements of electrolytes were always taken and conductivities were not measured if moisture contents were greater than 100 ppm If necessary, electrolyte moisture was reduced below 100 ppm by storage over 4A molecular sieves All electrolyte preparation was done in an inert atmosphere glove box or in a dry room with moisture less than 1% RH

Moisture measurements were made with a Mitsubishi CA-05 moisture analyzer based on the Karl Fischer method TGA measurements were made with a Dupont 951 TGA

Electrolyte conductivities were measured in 2-electrode glass conductivity cells with platinum electrodes Cells were filled in the glove box or dry room and then sealed with a ground glass joint and taken outside the glove box or dry room for the conductivity measurements The conductivity cells were well-cleaned between measurements on different electrolytes and were regularly re-platinized

Platinizing was done according to the procedure of Ives and Janz [13] Lead acetate was not used in the platinizing solution because of the possibility of introducing undesirable impurities The electrodes were immersed in 50% aqua regia (3:1:4 HCl:HNO<sub>3</sub>:H<sub>2</sub>O) for approximately 30–60 s, followed by a thorough rinse with deionized water Warm, concentrated nitric acid was then used to rinse the electrodes for approximately 5 min, again followed by a deionized water rinse The cell was then filled with a 0.01 M solution of H<sub>2</sub>SO<sub>4</sub>, and hydrogen was electrolytically generated, in turn, at each electrode using a PAR Model 173 potentiostat After another rinse with water, the cell was filled with a 0.1 M solution of chloroplatinic acid in 2 M HCl and the electrodes were electrolytically platinized The current was adjusted so as to produce a moderate evolution of hydrogen (about 20 mA cm<sup>-2</sup>) The polarity of the electrodes was reversed several times (every 2–5 min, about 10 min for each electrode) so that each electrode would be covered with a uniform black deposit The H<sub>2</sub>PtCl<sub>6</sub> solution was returned to its storage

TABLE 2  
Properties of solvents used in this studies

Solvent	Code used in this paper	Melting point (°C)	Boiling point (°C)	Viscosity ( $\eta$ ) (cP) (25 °C)	Dielectric constant ( $\epsilon$ ) (25 °C)
2-methyltetrahydrofuran	2-MeTHF	-75	79	0.46	6.2
3-methyl-2-oxazolidinone	3-Me-2-oxazolidinone	15.9		2.45	77.5
3-methylsulfolane	3-MeSulfolane	0	276		
Benzene	Benzene	5	80	0.602(20 °C)	2.284(20 °C)
$\gamma$ -Butyrolactone	$\gamma$ -Butyrolactone	-43	202	1.75	39.1
Cumene	Cumene	-96	153	0.791(20 °C)	2.38(20 °C)
Diglyme	Diglyme	-64	162	2.0(20 °C)	
<i>N,N</i> -Dimethylformamide	DMF	-61	158	0.79	36.7
Dimethoxyethane	DME	-69	85.2	0.45	5.5
Dimethoxymethane	DMM	-105	41		
Ethylene carbonate	EC	36.4	238	1.9(40 °C)	95.3
Ethyl benzene	Ethyl benzene	-95	136	0.678(20 °C)	2.412(20 °C)
Ethyl diglyme	Ethyl diglyme	-44	189	1.4(20 °C)	
Ethylmonoglyme	Ethylmonoglyme	-74	121	0.7(20 °C)	
Fluorotrichloromethane	Freon 11	-111	24		2.28(29 °C)
Methylene chloride	Methylene chloride	-97	40	0.44(21 °C)	9.14(20 °C)
Propylene carbonate	PC	-49	241	2.54	64.4
Propylsulfone	Propylsulfone	29	270		
Pseudocumene	Pseudocumene	-44	168	0.894(15 °C)	43.3(20 °C)
Sulfolane	Sulfolane	28.4	287.3	10.29(30 °C)	4.1
Tetraethylorthosilicate	TEOS		168		
Tetraglyme	Tetraglyme	-30	275	4.1(20 °C)	
Tetrahydrofuran	THF	-108	65	0.46	
Toluene	Toluene	-95	111	0.587(20 °C)	2.36(20 °C)
Triglyme	Triglyme	-45	216	3.8(20 °C)	$\approx 7$
<i>m</i> -Xylene	<i>m</i> -Xylene	-48	138	0.617(20 °C)	2.374(20 °C)
<i>o</i> -Xylene	<i>o</i> -Xylene	-24	144	0.809(20 °C)	2.270(20 °C)

If the measurements are at temperatures other than 25 °C, the temperature is listed

bottle, and the cell was rinsed with deionized water and stored with deionized water covering the electrodes until required for use

To determine the cell constant the conductance of a 0.01 M aqueous KCl solution was determined at 21, 25 and 30 °C. The cell constant was calculated using the known conductivities of 0.01 M KCl [14] and the relation

$$G = \frac{\sigma}{K} \quad (1)$$

where  $G$  is the measured conductance,  $\sigma$  is the conductivity, and  $K$  is the cell constant. Electrolyte conductivities were then determined by multiplying the conductance by the cell constant. Conductivities are accurate to  $\pm 5\%$ . Conductivities were measured using a YSI Model 35 conductance meter (Yellow Springs Instrument Co., Yellow Springs, Ohio, USA).

Temperatures from  $-60$  to  $-40$  °C were attained using liquid nitrogen and ethanol (or chloroform) in a Dewar flask as a temperature bath. Liquid nitrogen was added to the ethanol until the temperature, monitored by a Keithley Model 871 Digital Thermometer with a chromel–alumel thermocouple, was approximately  $-70$  °C. The conductivity cell was then placed in the bath until the level of the ethanol was above the level of the electrolyte inside the cell and the thermocouple was positioned so that it touched the glass between the two electrodes of the cell. The system was then allowed to equilibrate for at least 10 min and then conductance readings were taken as the system slowly warmed to the desired temperatures.

The above steps were repeated using a Haake A82 bath with an 85% ethanol/15% water medium for temperatures from  $-30$  to  $0$  °C, and a Neslab RTE-9DD bath with an ethylene glycol/water medium for temperatures between  $10$  and  $80$  °C. The system was equilibrated at each temperature for at least 15 min before conductance measurements were taken. All temperatures are accurate to  $\pm 1$  °C.

After the measurements were completed, the cell was emptied and rinsed several times, first with methanol and then with deionized water. The cell was then stored with deionized water covering the electrodes. Prior to the next measurement, the cell was thoroughly rinsed with methanol and dried at  $110$  °C. The cell was then taken to the glove box or dry room, rinsed with, and then filled with, the next electrolyte.

We measured the viscosities of some electrolyte solutions with a dropping ball viscometer at  $20$  °C. Specific gravities were measured using a 10.00 ml specific gravity bottle.

## Results

Tables 3, 4, 5, 6, and 7 give the conductivity versus temperature for non-aqueous electrolytes using  $\text{LiAsF}_6$ ,  $\text{LiPF}_6$ ,  $\text{LiCF}_3\text{SO}_3$ ,  $\text{LiN}(\text{CF}_3\text{SO}_2)_2$  and  $\text{LiBF}_4$ , respectively. Each of these Tables is organized as follows. Electrolytes are always designated alphabetically, e.g., those with mixtures of PC, EC

TABLE 3

Conductivities of  $\text{LiAsF}_6$ -based non-aqueous electrolytes versus temperature  
 f = frozen, sppt = salt precipitation

1	Electrolyte solvents		Vol % solvent										Conductivity ( $\text{mS cm}^{-1}$ ) at Celsius temperature indicated									
	2	3	4	1	2	3	4	-60	-50	-40	-30	-20	-10	0	20	40	60	80				
1.0	2-MeTHF			100				0.97	1.27	1.55	1.83	2.04	2.22	2.39	2.73							
1.0	2-MeTHF	DME	PC	35	35	15	15	0.89	1.24	2.14	4.59	6.31	8.24	10.37	15.23	20.64	26.01	31.19				
1.0	2-MeTHF	DME	PC	50	25	12.5	12.5	1.10	1.90	2.76	4.57	6.16	7.88	9.777	13.87	18.56	23.13	27.41				
1.0	2-MeTHF	DME	PC	25	25	25	25	0.39	0.95	1.82	3.29	4.90	6.73	8.79	13.49	18.64	23.93	29.37				
1.0	2-MeTHF	DMM	PC	35	30	17.5	17.5	0.63	1.18	2.12	3.46	4.78	6.29	7.92	11.42	14.87						
1.0	2-MeTHF	DMM	PC	15	50	7.5	7.5	f	f	0.92	2.03	3.22	4.10	5.03	6.80	8.58						
1.0	2-MeTHF	DMM	PC	25	50	12.5	12.5	0.60	1.07	1.95	3.19	4.38	5.71	7.05	9.85	12.64						
1.0	2-MeTHF	EC		50	50								f	6.57	10.14	14.09	18.26	22.50				
1.0	2-MeTHF	EC	Methylene chloride	15	7.5	7.5	7.5	1.52	2.14	2.85	3.66	4.46	5.20	5.98	7.56							
1.0	2-MeTHF	EC	Methylene chloride	25	12.5	50	12.5	1.63	2.50	3.58	4.94	6.16	7.49	8.82	11.54							
1.0	2-MeTHF	EC	Methylene chloride	35	17.5	30	17.5	1.03	1.74	2.71	3.82	5.08	6.48	7.97	11.22							
0.5	2-MeTHF	EC	PC	75	12.5	12.5		1.37	2.07	2.81	3.80	4.69	5.67	6.60	8.66	11.83	14.36	16.75				
1.0	2-MeTHF	EC	PC	25	37.5	37.5				1.48		2.24	3.34	4.62	7.84	11.60	15.78	20.10				
1.0	2-MeTHF	EC	PC	50	25	25		0.34	0.77	1.44	2.39	3.38	4.81	6.21	9.56	13.24	17.12					
1.0	2-MeTHF	EC	PC	75	12.5	12.5		1.15	1.80	2.54	3.55	4.67	5.88	6.94	9.90	12.76	15.52	18.18				
1.5	2-MeTHF	EC	PC	75	12.5	12.5		0.46	0.91	1.58	2.46	3.48	4.63	5.88	8.73	11.66	14.67	17.67				
2.0	2-MeTHF	EC	PC	75	12.5	12.5		0.05	0.17	0.44	0.91	1.55	2.37	3.40	5.95	8.88	12.06	15.38				
3.0	2-MeTHF	EC	PC	75	12.5	12.5		f	f	0.01	0.06	0.16	0.39	0.73	1.97	3.88	6.46	9.56				
1.0	2-MeTHF	EC	THF	35	17.5	17.5	30	1.27	2.09	3.15	4.63	6.12	7.73	9.49	13.32	17.05	20.77	24.61				
1.0	2-MeTHF	EC	THF	25	12.5	50	50	2.05	2.95	4.38	6.05	7.58	9.28	11.08	14.40	18.30	21.89	24.85				
1.0	2-MeTHF	EC	THF	15	7.5	7.5	7.5	2.84	3.69	5.27	7.22	8.79	10.43	12.17	15.35	18.58	21.38	23.80				
1.0	2-MeTHF	EC	Toluene	35	17.5	17.5	30	0.28	0.63	1.18	2.02	2.96	4.01	5.21	7.90							
1.0	2-MeTHF	Freon II		50	50			f	f	6.53	6.72	8.34	9.81	11.34	14.32							
1.0	2-MeTHF	Freon II		70	30					f	9.97	11.83	13.71	15.47	18.93							
1.0	2-MeTHF	Methylene chloride		30	70			1.08	1.40	1.70	1.86	2.12	2.37	2.60	2.96							

(continued)







TABLE 3 (continued)

LuAsF <sub>6</sub> (M)	Electrolyte solvents		Vol % solvent							Conductivity (mS cm <sup>-1</sup> ) at Celsius temperature indicated											
	1	2	3	4	1	2	3	4	-60	-50	-40	-30	-20	-10	0	20	40	60	80		
1.0	Methylene chloride	PC			30	70			0.26	0.69	1.40	1.95	2.93	4.11	5.50	8.57					
1.0	Methylene chloride	PC			50	50			0.82	1.64	2.66	3.20	4.33	5.61	6.99	9.83					
1.0	Methylene chloride	PC			70	30			1.11	1.43	1.96	2.63	3.36	4.17	5.03	6.94					
1.0	Methylene chloride	Sulfolane			25	75								f	2.64	4.24	6.55	9.22	11.22		
1.0	Methylene chloride	Sulfolane			50	50								f	3.68	7.23	9.46	10.66	boils		
1.0	Methylene chloride	Sulfolane	Trnglyme		50	25	25				3.38	4.41	5.81	7.16	10.51	13.75	boils				
1.0	Methylene chloride	Sulfolane	Trnglyme		25	50	25			0.43			1.27	1.85	2.69	5.43	8.17	11.25	13.40		
1.0	Methylene chloride	THF			30	70			f	5.43	6.92	8.28	9.84	11.22	12.48	14.57					
1.0	Methylene chloride	THF			50	50			5.24	6.64	8.23	9.98	11.38	12.62	13.63	15.06					
1.0	Methylene chloride	THF			70	30			4.39	5.36	6.34	7.29	8.02	8.64	9.12	9.81					
1.0	3-Methylsulfolane	Sulfolane			50	50						0.15	0.31	0.58	1.48	2.86	4.81	7.15			
0.2	PC	PC			100						0.65		0.93	1.33	1.80	2.93	4.26	5.69	7.21		
1.0	PC	PC			100				0.01	0.06	0.22	0.51	1.02	1.74	2.68	5.28	8.47	12.30	16.56		
1.0	PC	Sulfolane			50	50						0.59	1.00	1.67	3.53	5.93	8.96	12.60			
1.0	PC	Sulfolane	Trnglyme		10	45	45					0.44	0.87	1.45	3.17	5.52	8.32	11.52			
1.0	PC	Toluene			70	30			sppt	0.44	0.72	1.31	2.10	3.19	5.73						
1.0	Propylsulfone	Trnglyme			50	50							f	1.02	2.45	4.49	7.12	9.98			
0.75	Pseudocumene	Sulfolane	Trnglyme		25	50	25						0.91	1.29	2.68	4.49	6.64	9.01			
0.2	Sulfolane	Sulfolane			100									f	1.02	1.60	2.33	3.16			
0.5	Sulfolane	Sulfolane			100									f	1.01	1.90	3.07	4.57	6.26		
1.0	Sulfolane	Sulfolane			100								f	0.67	1.03	2.08	3.60	5.58	7.97		
1.5	Sulfolane	Sulfolane			100								f	0.67	1.03	2.08	3.60	5.58	7.97		
2.0	Sulfolane	Sulfolane			100									f	1.62	3.04	5.05	7.56			
																			f	4.11	6.46



TABLE 4  
Conductivities of  $\text{LiPF}_6$ -based non-aqueous electrolytes versus temperature  
f = frozen, sppt = salt precipitation

$\text{LiPF}_6$ (M)	Electrolyte solvents			Vol % solvent			Conductivity ( $\text{mS cm}^{-1}$ ) at Celsius temperature indicated										
	1	2	3	1	2	3	-60	-50	-40	-30	-20	-10	0	20	40	60	80
1.0	2-MeTHF	EC	PC	75	12.5	12.5	0.95	1.61	2.43	3.41	4.46	5.56	6.75	9.24	11.64	14.00	16.22
1.0	EC	PC	PC	15	85		0.01	0.06	0.21	0.56	1.12	1.90	2.92	5.64	8.95	12.80	16.88
1.0	EC	PC	PC	50	50		0.01	0.05	0.23	0.71	1.36	2.26	3.46	6.56	10.34	14.63	19.35

TABLE 5  
Conductivities of  $\text{LiCF}_3\text{SO}_3$ -based non-aqueous electrolytes versus temperature  
f = frozen, sppt = salt precipitation

$\text{LiCF}_3\text{SO}_3$ (M)	Electrolyte solvents			Vol % solvents			Conductivity ( $\text{mS cm}^{-1}$ ) at Celsius temperature indicated										
	1	2	3	1	2	3	-60	-50	-40	-30	-20	-10	0	20	40	60	80
1.0	2-MeTHF	EC	PC	75	12.5	12.5	0.25	0.39	0.50	0.74	0.93	1.23	1.34	1.78	2.31	2.81	3.30
1.0	DME	EC	EC	50	50					f	4.35	5.32	7.41	9.43	11.44	13.29	
1.0	DME	PC	PC	50	50					2.61	3.37	4.17	5.88	7.46	9.07	10.61	
1.0	EC	Ethylmonoglyme	EC	50	50							f	3.59	4.95	6.45	7.94	
1.0	EC	PC	PC	50	50		0.01	0.02	0.31	0.55	0.85	1.24	2.22	3.45	4.88	6.43	

TABLE 6

Conductivities of  $\text{LiN}(\text{CF}_3\text{SO}_2)_2$ -based non-aqueous electrolytes versus temperature

f = frozen, sppt = salt precipitation

(M)	Electrolyte solvents			Conductivity ( $\text{mS cm}^{-1}$ ) at Celsius temperature indicated																	
	1	2	3	1	2	3	1	2	3	-60	-50	-40	-30	-20	-10	0	20	40	60	80	
1.0	2-MeTHF	EC	PC	75	12.5	12.5						2.07		3.40	4.28	5.12	7.06	8.71	10.41	12.02	
1.0	$\gamma$ -Butyrolactone	DME		50	50							4.30	5.72	7.35	9.19	13.13	17.33	21.60	25.43		
1.0	$\gamma$ -Butyrolactone	Ethylmonoglyme		50	50							2.50	3.58	4.81	6.18	9.24	12.47	15.76	18.96		
1.0	DME	EC		50	50							f	f	5.46	7.87	12.08	16.58	21.25	25.97		
1.0	DME	PC		50	50								3.92	5.44	7.19	11.23	15.51	19.88	24.30		
1.0	EC	Ethylmonoglyme		50	50								f	4.03	5.49	8.70	12.07	15.74	19.47		
1.0	EC	PC		50	50							sppt	0.28	0.67	1.21	1.94	2.80	5.12	7.69	10.70	13.86
1.0	Ethylmonoglyme	Sulfolane		50	50							0.22	0.39	0.78	1.27	1.92	2.67	4.58	6.75	8.99	11.29
0.75	Sulfolane	Triglyme		50	50							0.23	0.45	0.80	1.24	2.58	4.22	6.30	8.60		

TABLE 7

Conductivities of  $\text{LiBF}_4$ -based non-aqueous electrolytes versus temperature

f = frozen, sppt = salt precipitation

(M)	Electrolyte solvents			Conductivity ( $\text{mS cm}^{-1}$ ) at Celsius temperature indicated																
	1	2	3	1	2	3	1	2	3	-60	-50	-40	-30	-20	-10	0	20	40	60	80
1.0	2-MeTHF	EC	PC	75	12.5	12.5								0.38	0.62	0.92	1.64	2.53	3.43	4.29
1.0	EC	PC		50	50									1.11	1.71	2.41	4.25	6.27	8.51	10.79
0.5	Sulfolane	Triglyme		50	50					0.02	0.05	0.19	0.64	0.38	0.62	0.92	4.29	3.43	2.53	1.64

and benzene appear with benzene as solvent 1 since it is alphabetically first, then EC as solvent 2 and PC as solvent 3. The rows in the Tables are then alphabetized by solvent 1. Electrolytes with the same solvent 1 are then alphabetized by solvent 2 and so on. Numerals have been given precedence over alphabetic characters in our organization, so 2-MeTHF appears before benzene, for example. The Tables list the volume percent of each solvent in the mixed solvent system before addition of the salt. At every Table entry where there are data, the electrolyte is a single-phase homogeneous liquid. We stopped taking data when the conductivity became too low to be useful in practical cells, when the electrolyte froze (denoted by f in the Tables), or when precipitation of salt from solution was observed (denoted by sppt).

We have found that electrolytes based on EC, PC, EC/PC and sulfolane are the most useful in rechargeable Li cells. We have extracted these from Table 3. Table 8 lists conductivities of electrolytes with equal volumes of EC and PC. EC and PC are the 'primary solvents' in these electrolytes and are labelled solvents 1 and 2 in Table 8. Table 8 is alphabetized by solvents 3 and 4. Table 9 lists those electrolytes from Table 3 with pure EC as a primary solvent. Tables 10 and 11 list those electrolytes with PC and with sulfolane, respectively, as primary solvents. Tables 9, 10, and 11 are alphabetized by solvents 2, 3, and 4, with the primary solvent as solvent 1.

Figure 2 shows the conductivity of 1 M solutions of each of the five salts in equal volumes of EC and PC.  $\text{LiPF}_6$  electrolytes always have the highest conductivity. Conductivities of electrolytes with  $\text{LiCF}_3\text{SO}_3$  are always less than the other salts by about a factor of 2. The imide salt,  $\text{LiN}(\text{CF}_3\text{SO}_2)_2$  shows conductivity about equal to  $\text{LiAsF}_6$  and excellent thermal stability (Fig 1).

Figure 3 shows the conductivities of 1 M solutions of each of the five salts in 2-MeTHF/EC/PC (75%/12.5%/12.5%). The 2-MeTHF is responsible for the increase in conductivity at low temperature when compared with Fig 2. These data mirror those of Fig 2, except that  $\text{LiBF}_4$  has a lower conductivity in this electrolyte. The data in Tables 3 and 6 show that  $\text{LiAsF}_6$  and  $\text{LiN}(\text{CF}_3\text{SO}_2)_2$  electrolytes, using the same solvents, always have similar conductivity.

Figure 4 shows the dependence of conductivity on percentage PC in 1 M  $\text{LiAsF}_6$ /EC/PC electrolytes. 1 M  $\text{LiAsF}_6$ /EC is liquid at 20 °C because of the freezing point depression, but is solid at 0 °C. Our experience, and that in the literature [8], show that EC-based electrolytes give longer cycle life (higher Li cycling efficiencies) than PC-based electrolytes. We have found similar cycle life for Li/MoS<sub>2</sub> cells using 1 M  $\text{LiAsF}_6$ /EC/PC (50/50) and 1 M  $\text{LiAsF}_6$ /EC/PC (15/85), suggesting that only a small amount of EC is needed to give the cycle life enhancement over pure PC.

Figures 5, 6, 7, and 8 show the dependence of conductivity on molarity of  $\text{LiAsF}_6$  in EC/PC (50/50), EC/PC (15/85), 2-MeTHF/EC/PC (75/12.5/12.5), and sulfolane, respectively. In each of these solvent systems the maximum conductivity is near 1.0 M. The variation of conductivity with salt molarity could be analyzed with the Casteel-Amis equation as was done in ref 6.

TABLE 8

Conductivities of LiAsF<sub>6</sub>-based electrolytes with EC/PC primary solvents versus temperature  
 f = frozen, sppt = salt precipitation

LiAsF <sub>6</sub> (M)	Electrolyte solvents				Vol % solvent																	Conductivity (mS cm <sup>-1</sup> ) at Celsius temperature indicated																		
	1	2	3	4	1	2	3	4	4	-60	-50	-40	-30	-20	-10	0	20	40	60	80	1	2	3	4	4	-60	-50	-40	-30	-20	-10	0	20	40	60	80				
1.0	EC	PC			50	50						0.64	1.15	1.96	3.04	5.94	9.55	13.86	18.49																					
1.0	EC	PC	Benzene		30	30	40							sppt	3.79	6.74	10.12	13.89	17.66																					
1.0	EC	PC	2-MeTHF		37.5	37.5	25					1.48	2.24	3.34	4.62	7.84	11.00	15.78	20.10																					
1.0	EC	PC	2-MeTHF		25	25	50		0.34	0.77	1.44	2.39	3.38	4.81	6.21	9.56	13.24	17.12																						
1.0	EC	PC	2-MeTHF	DME	12.5	12.5	75					3.55	4.67	5.88	6.94	9.90	12.76	15.52	18.18																					
1.0	EC	PC	2-MeTHF	DME	12.5	12.5	50	25	1.15	1.80	2.76	4.57	6.16	7.88	9.77	13.87	18.56	23.13	27.41																					
1.0	EC	PC	2-MeTHF	DME	15	15	35	35	0.89	1.24	2.14	4.59	6.31	8.24	10.37	15.23	20.64	26.01	31.19																					
1.0	EC	PC	2-MeTHF	DME	25	25	25	25	0.39	0.95	1.82	3.29	4.90	6.73	8.79	13.49	18.64	23.93	29.37																					
1.0	EC	PC	2-MeTHF	DMM	7.5	7.5	15	50	f	0.92	2.03	3.22	4.10	5.03	6.80	8.58																								
1.0	EC	PC	2-MeTHF	DMM	12.5	12.5	25	50	0.60	1.07	1.95	3.19	4.38	5.71	7.05	9.85	12.64																							
1.0	EC	PC	2-MeTHF	DMM	17.5	17.5	35	30	0.63	1.18	2.12	3.46	4.78	6.29	7.92	11.42	14.87																							
1.0	EC	PC	2-MeTHF	Methylene chloride	7.5	7.5	15	70	1.52	2.14	2.85	3.66	4.46	5.20	7.56																									
1.0	EC	PC	2-MeTHF	THF	7.5	7.5	15	70	2.84	3.69	5.27	7.22	8.79	10.43	12.17	15.35	18.58	21.38	23.80																					
1.0	EC	PC	2-MeTHF	THF	12.5	12.5	25	50	2.05	2.95	4.38	6.05	7.58	9.28	11.08	14.40	18.30	21.89	24.85																					
1.0	EC	PC	2-MeTHF	THF	17.5	17.5	35	30	1.27	2.09	3.15	4.63	6.12	7.73	9.49	13.32	17.05	20.77	24.61																					
1.0	EC	PC	2-MeTHF	Toluene	17.5	17.5	35	30	0.28	0.63	1.78	2.92	4.01	5.21	7.90																									
1.0	EC	PC	Diglyme		25	25	50							sppt	3.39	4.78	8.37	12.63	17.11	21.94																				
1.0	EC	PC	DME		25	25	50		0.28	0.57	1.07	3.35	5.02	7.02	9.23	14.40	19.87	25.75	31.44																					
1.0	EC	PC	Methylene chloride		15	15	70		0.51	1.02	1.67	2.60	3.39	4.24	5.15	6.97																								
1.0	EC	PC	Methylene chloride		25	25	50		0.76	1.44	2.31	3.19	4.39	5.70	7.19	10.41																								
1.0	EC	PC	Methylene chloride		35	35	30		0.22	0.53	1.11	2.04	3.15	4.33	5.81	9.32																								
1.0	EC	PC	Methylene chloride	THF	7.5	7.5	70	15	2.64	3.62	4.64	5.69	6.72	7.72	8.68	10.52																								
1.0	EC	PC	Methylene chloride	THF	12.5	12.5	50	25	2.54	3.76	5.13	6.69	8.26	9.84	11.45	14.79																								
1.0	EC	PC	Methylene chloride	THF	17.5	17.5	30	35	1.77	2.80	4.10	5.65	7.21	8.93	10.68	14.58																								
1.0	EC	PC	chloride		37.5	37.5	25					1.55	2.53	3.64	6.58	9.93	13.90	17.74																						
1.0	EC	PC	Toluene		25	25	50		0.03	0.20	0.59	1.19	2.01	3.08	6.01	9.64	13.79	18.29																						

TABLE 9  
 Conductivities of  $\text{LiAsF}_6$ -based electrolytes with EC primary solvent versus temperature  
 f = frozen, sppt = salt precipitation

$\text{LiAsF}_6$ (M)	Electrolyte solvents		Vol % solvent		Conductivity ( $\text{mS cm}^{-1}$ ) at Celsius temperature indicated										
	1	2	1	2	-60	-50	-40	-30	-20	-10	0	20	40	60	80
1.0	EC		100								f	6.97	11.00	15.72	20.67
1.0	EC	2-MeTHF	50	50						f	6.57	10.14	14.09	18.26	22.50
1.0	EC	DME	50	50		f	5.27	7.23	9.50	14.52	20.64	26.65	32.57		
1.0	EC	Ethylmonoglyme	50	50			f	4.75	6.49	10.67					
1.0	EC	Sulfolane	50	50		0.37	0.71	1.27	1.98	4.12	6.87	10.22	14.02		
1.0	EC	Triglyme	50	50		1.30	2.26	3.40	6.55	10.54	14.90	19.74			



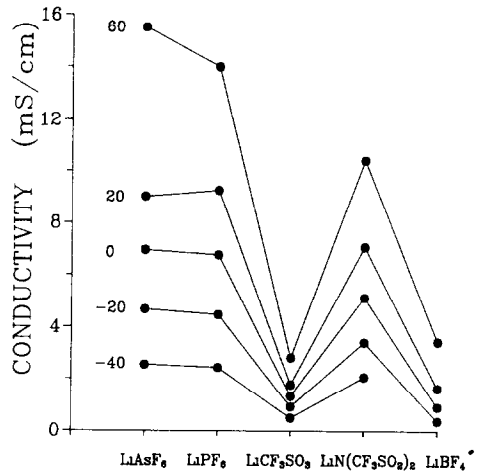
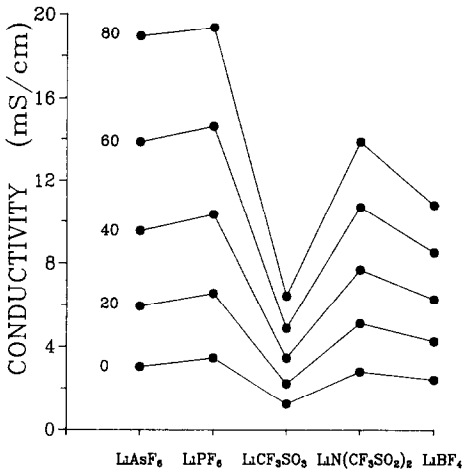
TABLE 10  
 Conductivities of LiAsF<sub>6</sub>-based electrolytes with PC primary solvent versus temperature  
 f = frozen, sppt = salt precipitation

LiAsF <sub>6</sub> (M)	Electrolyte solvents		Vol % solvent		Conductivity (mS cm <sup>-1</sup> ) at Celsius temperature indicated										
	1	2	1	2	-60	-50	-40	-30	-20	-10	0	20	40	60	80
0.2	PC		100					0.65	0.93	1.33	1.80	2.94	4.26	5.69	7.21
1.0	PC		100					0.51	1.02	1.74	2.68	5.28	8.47	12.30	16.56
1.0	PC	DME	50	50			f	3.28	4.43	6.24	8.37	13.15	18.46	23.92	28.18
4.0	PC	DME	50	50			f	0.01	0.08	0.27	0.70	2.74	6.65	12.37	19.49
1.0	PC	Ethylmonoglyme	50	50				2.09	2.89	4.27	5.83	9.49	13.54	17.86	22.01
1.0	PC	Methylene chloride	30	70				1.11	1.96	3.36	4.17	5.03	6.94		
1.0	PC	Methylene chloride	50	50				0.82	1.64	2.66	3.20	4.33	5.61	6.99	9.83
1.0	PC	Methylene chloride	70	30				0.26	0.69	1.40	1.95	2.93	4.11	5.50	8.57
1.0	PC	Sulfolane	50	50								0.59	1.00	1.67	3.53
1.0	PC	Toluene	70	30				sppt	0.44	0.72	1.31	2.10	3.19	5.73	
													5.93	8.96	12.60

TABLE 11  
 Conductivities of LiAsF<sub>6</sub>-based electrolytes with sulfolane primary solvent versus temperature  
 f = frozen, sppt = salt precipitation

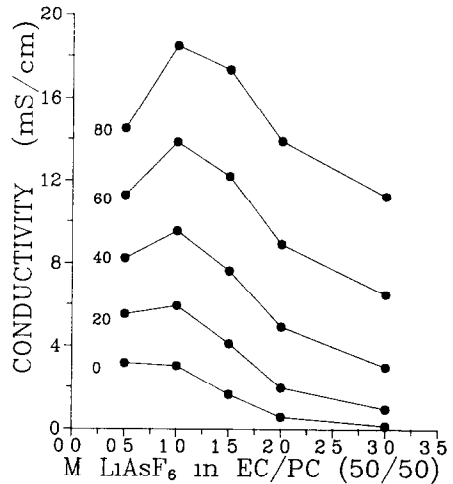
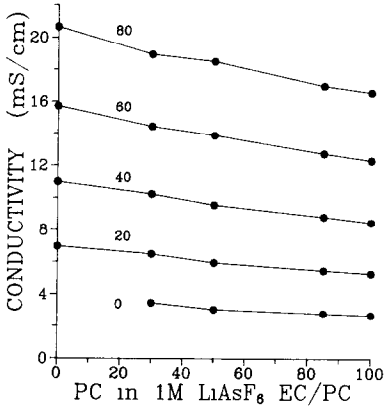
LiAsF <sub>6</sub> (M)	Electrolyte solvents			Vol % solvent			Conductivity (mS cm <sup>-1</sup> ) at Celsius temperature indicated										
	1	2	3	1	2	3	-60	-50	-40	-30	-20	-10	0	20	40	60	80
1.0	Sulfolane			100									1.03	2.08	3.60	5.58	7.97
1.0	Sulfolane	2 MeTHF		50	50						f	0.67	2.50	5.15	7.28	9.46	11.66
1.0	Sulfolane	3-Mesulfolane		50	50		0.20	0.42	0.77	1.24	1.82	2.50	3.27	5.15	7.28	9.46	11.66
1.0	Sulfolane	Benzene		60	40						0.15	0.31	0.58	1.48	2.86	4.81	7.15
1.0	Sulfolane	Cumene	Triglyme	50	25	25			0.36	0.56	0.95	1.42	2.85	4.73	6.90	9.32	12.24
1.0	Sulfolane	Diglyme		50	50						f	1.64	3.43	5.85	8.75	12.24	
1.0	Sulfolane	Diglyme		60	40						sppt	2.88	5.14	7.93	12.93		
1.0	Sulfolane	DME		50	50						sppt	1.84	2.85	4.13	7.21	9.69	14.81
1.0	Sulfolane	DME		60	40						sppt	1.29	2.11	3.13	5.82	9.14	13.02
1.0	Sulfolane	Diglyme	DME	50	25	25					sppt	1.28	2.03	2.94	5.43	8.50	12.02
1.0	Sulfolane	Diglyme	Ethyldiglyme	50	25	25			sppt		0.43	0.86	1.39	3.04	5.33	8.14	11.34
1.0	Sulfolane	Diglyme	Triglyme	50	25	25		sppt	0.07	0.43	0.80	1.31	2.94	5.17	8.02	11.16	
1.0	Sulfolane	DME	Triglyme	50	15	35		sppt	0.14	0.30	0.68	1.17	1.82	3.74	6.25	9.23	12.34
1.0	Sulfolane	DME	Triglyme	50	25	25		sppt	0.23	0.56	0.97	1.61	2.41	4.62	7.52	10.82	14.40
1.0	Sulfolane	Ethylbenzene	Triglyme	35	30	35	sppt	0.08	0.21	0.44	0.83	1.35	1.98	3.84	6.05	8.60	11.42
0.75	Sulfolane	Ethylbenzene	Triglyme	50	25	25			0.43	0.77	1.24	1.82	3.44	5.26	7.38	10.20	
1.0	Sulfolane	Ethyldiglyme	Triglyme	50	50			sppt	0.10	0.19	0.40	0.74	1.21	2.75	4.73	7.25	11.66
1.0	Sulfolane	Ethyldiglyme		50	50				0.60	1.11	1.78	2.57	4.76	7.28	10.11	13.01	
1.0	Sulfolane	EC		50	50				0.37	0.71	1.27	1.98	4.12	6.87	10.22	14.02	
1.0	Sulfolane	EC	Triglyme	25	25	50			0.37	0.73	1.33	2.11	4.45	7.36	10.70	14.66	
1.0	Sulfolane	EC	Triglyme	40	20	40			0.32	0.54	1.00	1.62	3.58	6.15	9.40	13.04	
1.0	Sulfolane	EC	Triglyme	45	10	45		0.02	0.07	0.19	0.44	0.83	1.38	3.09	5.45	8.40	11.69
1.0	Sulfolane	EC	Triglyme	50	25	25		0.03	0.11	0.27	0.59	1.05	1.68	3.61	6.20	9.37	12.98
1.0	Sulfolane	Methylene chloride		50	50						f	3.68	7.23	9.46	10.66	boils	
1.0	Sulfolane	Methylene chloride		75	25						f	2.64	4.24	6.55	9.22	11.22	
1.0	Sulfolane	Methylene chloride	Triglyme	25	50	25			3.38	4.41	5.81	7.16	10.51	13.75	boils		

1 0	Sulfolane	Methylene chloride	Triglyme	50	25	25	0.43	1.27	1.85	2.69	5.43	8.17	11.25	13.40
1 0	Sulfolane	PC		50	50			0.59	1.00	1.67	3.53	5.93	8.96	12.60
1 0	Sulfolane	PC	Triglyme	45	10	45		0.44	0.87	1.45	3.17	5.52	8.32	11.52
0.75	Sulfolane	Pseudocumene	Triglyme	50	25	25		0.91	1.29	2.68	4.49	6.64	9.01	
0.5	Sulfolane	Tetraglyme		50	50		sppt	0.09	0.43	0.74	1.68	2.99	4.67	6.61
0.75	Sulfolane	Tetraglyme		50	50		0.03	0.08	0.20	0.43	0.73	1.83	3.44	5.52
1 0	Sulfolane	Tetraglyme		25	75			0.19	0.42	0.76	1.93	3.67	5.93	8.64
1 0	Sulfolane	Tetraglyme		50	50		sppt	0.02	0.06	0.16	0.36	0.66	1.75	3.50
0.75	Sulfolane	Toluene	Triglyme	50	25	25		0.83	1.34	1.96	3.73	5.81	8.23	10.82
1 0	Sulfolane	Toluene	Triglyme	25	50	25		1.43	2.11	2.88	4.85	7.03	9.38	11.75
1 0	Sulfolane	Toluene		70	30					sppt	3.23	5.06	7.29	9.70
0.5	Sulfolane	Triglyme		50	50		sppt	0.36	0.75	1.05	2.19	3.70	5.78	7.90
0.75	Sulfolane	Triglyme		50	50			0.40	0.68	1.10	2.48	4.29	6.64	9.23
1 0	Sulfolane	Triglyme		50	50		sppt	0.14	0.32	0.63	1.05	2.47	4.45	6.97
1.5	Sulfolane	Triglyme		50	50		0.01	0.16	0.68	1.87	3.82	6.55	9.86	
0.75	Sulfolane	Triglyme	<i>m</i> -Xylene	50	25	25	sppt	0.37	0.48	1.34	1.71	3.35	5.30	7.66
0.75	Sulfolane	Triglyme	<i>o</i> -Xylene	50	25	25	0.27	0.52	0.91	1.39	2.85	4.70	6.83	9.34



**Fig 2** Conductivity of 1 M electrolytes in EC/PC (50/50) Celsius temperatures are indicated on the graph The solid lines are guides to the eye

**Fig 3** Conductivity of 1 M electrolytes in 2-MeTHF/EC/PC (75/12.5/12.5) Celsius temperatures are indicated on the graph The solid lines are guides to the eye



**Fig 4** Conductivity of 1 M LiAsF<sub>6</sub>/EC/PC mixed electrolytes as a function of vol % PC Celsius temperatures are indicated on the graph The solid lines are guides to the eye

**Fig 5** Conductivity of LiAsF<sub>6</sub>/EC/PC (50/50) electrolytes as a function of molality Celsius temperatures are indicated on the graph The solid lines are guides to the eye

Figure 9 shows that by adding triglyme to sulfolane, the liquid range of the electrolyte is increased For example, 0.2 M LiAsF<sub>6</sub> and 1.5 M LiAsF<sub>6</sub> in sulfolane are frozen at 0 °C, while these solutions in sulfolane/triglyme (50/50) are liquid at 0 °C (Table 3) The conductivity enhancement through adding triglyme is small because triglyme is a relatively viscous solvent (Table

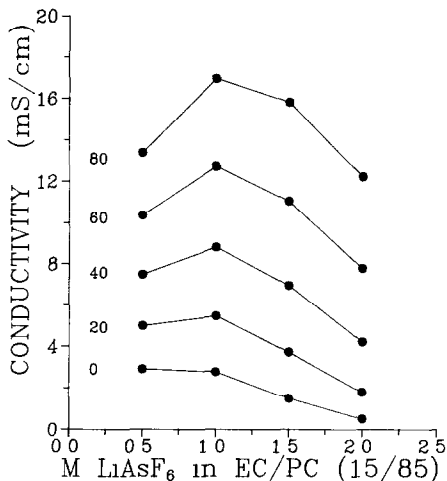


Fig 6 Conductivity of  $\text{LiAsF}_6/\text{EC}/\text{PC}$  (15/85) electrolytes as a function of molarity Celsius temperatures are indicated on the graph The solid lines are guides to the eye

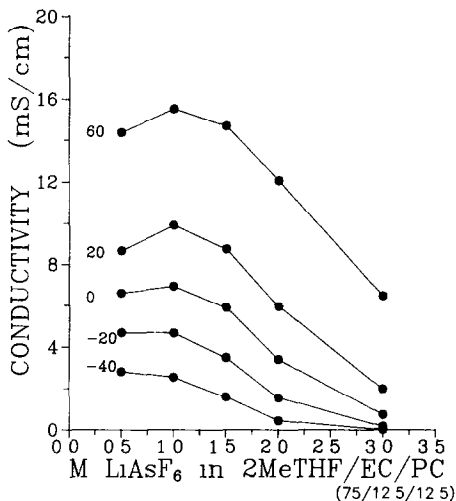


Fig 7 Conductivity of  $\text{LiAsF}_6/2\text{-MeTHF}/\text{EC}/\text{PC}$  (75/12.5/12.5) electrolytes as a function of molarity Celsius temperatures are indicated on the graph The solid lines are guides to the eye

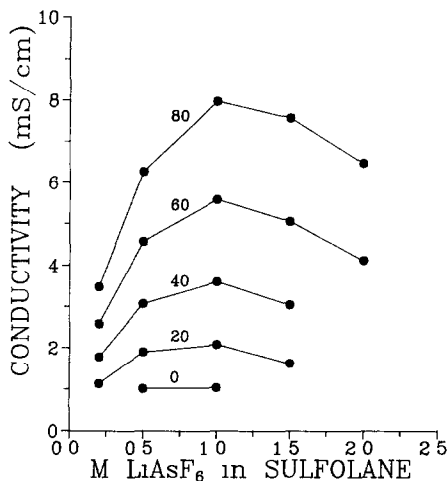


Fig 8 Conductivity of  $\text{LiAsF}_6/\text{sulfolane}$  electrolytes as a function of molarity Celsius temperatures are indicated on the graph The solid lines are guides to the eye

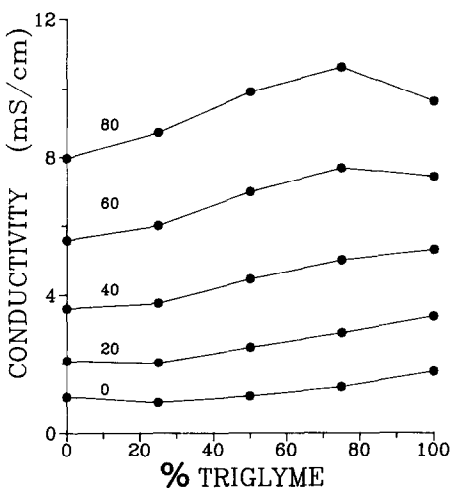


Fig 9 Conductivity of 1 M  $\text{LiAsF}_6/\text{sulfolane}/\text{triglyme}$  electrolytes as a function of vol % triglyme Celsius temperatures are indicated on the graph The solid lines are guides to the eye

2) Additions of the other methylglymes ( $\text{CH}_3\text{O}(\text{C}_2\text{H}_4\text{O})_n\text{CH}_3$  for  $n=1, 2, 3, 4$ ) also improve the liquid range of sulfolane/glyme electrolytes Additions of DME ( $n=1$ ) and diglyme ( $n=2$ ) cause a significant conductivity enhancement (Table 11), since they have relatively low viscosity

Table 12 gives the viscosity,  $\eta$ , of 1 M LiAsF<sub>6</sub> solutions in sulfolane/*n*-glyme (50/50) electrolytes at 20 °C. Figure 10 shows the electrolyte conductivity at 20 °C plotted versus  $1/\eta$ . If we assume the diffusion of the ions obeys Stokes law, then the conductivity is

$$\sigma = \sum_i \frac{(z_i)^2 (F) c_i}{6\pi\eta r_i} \quad (2)$$

where  $z_i$  is the charge on the  $i$ th ionic species,  $F$  is the Faraday constant,  $c_i$  is the molar concentration of the  $i$ th ion, and  $r_i$  is the Stokes radius of the  $i$ th ionic species [16]. According to eqn (2), plots of  $\sigma$  versus  $1/\eta$  should be linear if the Stokes radius and the molarity are constant. The linearity shown for the sulfolane/glyme electrolytes in Fig. 10 suggests that

TABLE 12  
Viscosity of sulfolane/glyme electrolytes at 20 °C

Electrolyte	Specific gravity (g cm <sup>-3</sup> ) (20 °C)	Viscosity (cP) (20 °C)
1 M LiAsF <sub>6</sub> /sulfolane	1.3968 ± 0.0003	29.5 ± 0.3
1 M LiAsF <sub>6</sub> /DME/sulfolane (50/50)	1.2331 ± 0.0003	3.75 ± 0.05
1 M LiAsF <sub>6</sub> /diglyme/sulfolane (50/50)	1.2583 ± 0.0003	8.06 ± 0.05
1 M LiAsF <sub>6</sub> /sulfolane/triglyme (50/50)	1.2730 ± 0.0003	12.0 ± 0.1
1 M LiAsF <sub>6</sub> /sulfolane/tetraglyme (50/50)	1.2874 ± 0.0003	16.9 ± 0.1

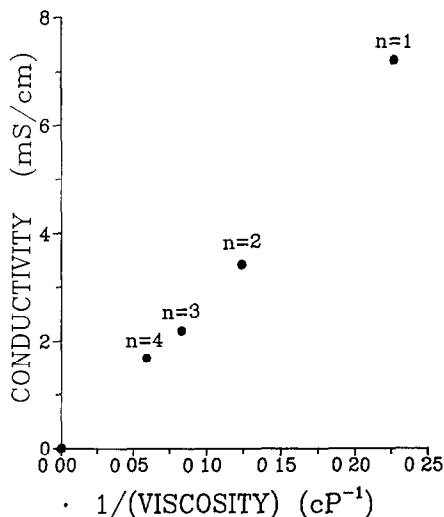


Fig. 10 Conductivity of 1 M LiAsF<sub>6</sub>/sulfolane/CH<sub>3</sub>O(C<sub>2</sub>H<sub>4</sub>O)<sub>n</sub>CH<sub>3</sub> (50/50) electrolytes at 20 °C as a function of reciprocal electrolyte viscosity. Data for each  $n$  (DME,  $n=1$ , diglyme,  $n=2$ , triglyme,  $n=3$ , tetraglyme,  $n=4$ ) is indicated on the graph.

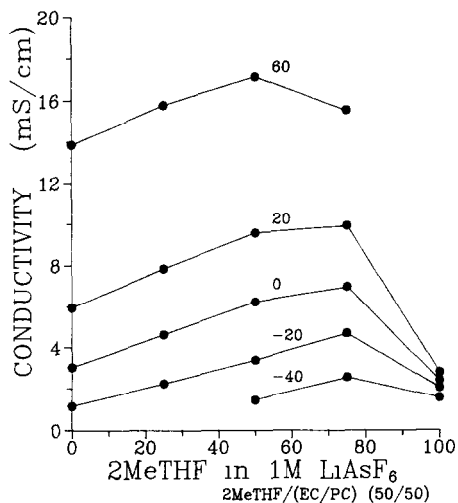


Fig 11 Conductivity of 1 M  $\text{LiAsF}_6$ /2-MeTHF/(EC/PC) (50/50) electrolytes as a function of vol% 2-MeTHF Celsius temperatures are indicated on the graph Solid lines are guides to the eye

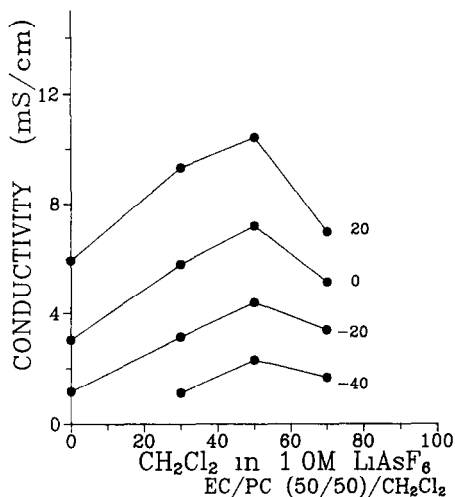


Fig 12 Conductivity of 1 M  $\text{LiAsF}_6$ /(EC/PC) (50/50)/methylene chloride electrolytes as a function of vol% methylene chloride Celsius temperatures are indicated on the graph Solid lines are guides to the eye

the glyme number does not affect the Stokes radius of the  $\text{Li}^+$  and  $\text{AsF}_6^-$  ions in this solvent system The importance of minimizing solution viscosity to maximize conductivity is illustrated by Fig 10

Figures 11 and 12 show the effect of additions of 2-MeTHF and methylene chloride, respectively, to EC/PC electrolytes The viscosities of 2-MeTHF and methylene chloride are approximately equal and are much smaller than the viscosities of EC or PC (Table 2) so, according to eqn (2), we expect additions of both to enhance the conductivity of EC/PC electrolytes The conductivity drops at high concentrations of 2-MeTHF and methylene chloride because the viscosity is no longer the dominant parameter 2-MeTHF and methylene chloride differ in that  $\text{LiAsF}_6$  is easily soluble to beyond 1 M in the former and is soluble to less than 0.05 M in the latter EC/PC-based electrolytes with more than 70% methylene chloride exhibit multi-phase behaviour because of this poor solubility Small additions of low viscosity aromatics to EC/PC- and sulfolane-based electrolytes show similar increases in electrolyte conductivity (Table 3)

## Summary

We have listed the conductivities and some properties of electrolytes, salts, and solvents of importance for rechargeable Li batteries This work is part of ongoing electrolyte research at Moli Energy (1990) Limited and we

feel it is a useful reference for workers in the field We emphasize the importance of electrolyte viscosity in determining electrolyte conductivity and have shown how some non-traditional additives such as aromatics and halogenated solvents can improve electrolyte conductivity

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