Redox-active Cavitand Host Molecules containing Multiple Ferrocenyl Redox Centres: Syntheses, Crystal Structure, Molecular Mechanics Calculations, and Electrochemical Properties†

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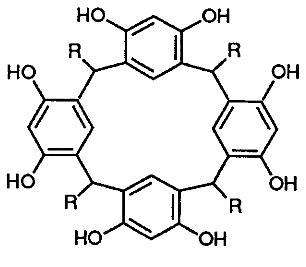
The design, synthesis, *X*-ray crystal structure, molecular mechanics calculations, and electrochemical properties of novel redox-active cavitand host molecules containing multiple ferrocenyl redox centres are described. The acid-catalysed condensation of ferrocenecarbaldehyde (**1**) with 1,3-dihydroxybenzene (**2**) afforded a new phenolic macrocycle 2,8,14,20-tetraferrocenylpentacyclo[19.3.1.$1^{3,7}$.$1^{9,13}$.$1^{15,19}$]octacosa-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,23-dodecaen-4,6,10,12,16,18,22,24-octol (**3**) which on reaction with bromochloromethane gave the first rigid redox-active cavitand host molecule (**4**) containing four ferrocenyl redox centres. The reaction of compound (**3**) and the corresponding 2,8,14,20-tetramethyl octol (**5**) with 1,1′-bis(chlorocarbonyl)ferrocene (**6**) gave the respective redox cavitands (**7**) and (**8**) with the ferrocene moieties lining the wall of the cavitand cavity. The single-crystal *X*-ray structure of compound (**4**) reveals a dichloromethane guest molecule within the cavitand host cavity. Molecular mechanics calculations performed on the complexes of cavitand (**4**) with dichloromethane, toluene, and carbon dioxide suggest the cavitand cavity will only allow limited inclusion of small guest species. Electrochemical studies show the multiple ferrocene centres present in (**4**) and (**7**) to undergo independent reversible one-electron oxidations in dichloromethane. The addition of dichloromethane to or bubbling of carbon dioxide through electrochemical dimethylformamide solutions of (**7**) produced no significant changes in the cyclic voltammogram of (**7**).

The acid-catalysed condensation of 1,3-dihydroxybenzene with a variety of aldehydes was first performed by Michael[1] in 1883. However, the correct structure of the crystalline products formed was not proposed until 1940,[2] and conclusive *X*-ray crystallographic determinations were not obtained until 1968.[3] The reaction yields a cyclic octol (I) which can adopt a number of configurational isomers. Hogberg has made a careful study of the reactions of acetaldehyde[4] and benzaldehyde[5] with 1,3-dihydroxybenzene and found that only two stereoisomers were formed in reasonable yields. The kinetic product, the *cis-trans-cis* isomer, has a chair-type conformation, which can *in situ* be converted into the less-soluble thermodynamic product, the all-*cis* stereoisomer, which has a boat-type conformation. Further recent studies of a number of condensations by Cram and co-workers[6] indicate that aliphatic aldehydes and 1,3-dihydroxybenzene or 1,3-dihydroxy-2-methylbenzene give good yields of the all-*cis* isomer, while benzaldehyde or 4-substituted benzaldehydes and the same resorcinols produce the all-*cis* isomer, the *cis-trans-cis* isomer, or a mixture of the two. Interestingly, condensation with lipophilic aldehydes such as heptanal or dodecanal yield a third *cis-trans-trans* isomer, possessing a diamond-type configuration.[7]



(I) R = Me or Ph

Cram has subsequently rigidified the parent octol (I; R = Me) by treatment with bromochloromethane,[8] alkaneditosylates,[8] and 2,3-dichloro-1,4-diazanaphthalene[9] to produce 'cavitands',[10] synthetic organic host molecules that contain inflexible hydrophobic cavities of dimensions large enough to include simple organic and inorganic guest species. Indeed these cavitand molecules form solvates with guest molecules such as acetonitrile, chloroform, benzene, and toluene.[8,11] The incorporation of redox-active centres into these preorganised host compounds will lead to prototypes of new molecular sensory devices capable of electrochemically recognising the inclusion of a guest in the cavitand cavity[12] (Figure 1). Such compounds may also ultimately serve as a new class of redox catalyst, polarising included guest species by means of electron-density transfer to or from the redox-active centre, thus activating the guest towards reaction with an incoming substrate.

The organometallic ferrocene moiety is an attractive redox-active centre to be integrated into preorganised host molecules

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† *Supplementary data available:* see Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1990, Issue 1, pp. xix—xxii.

Non-S.I. unit employed: cal = 4.184 J.

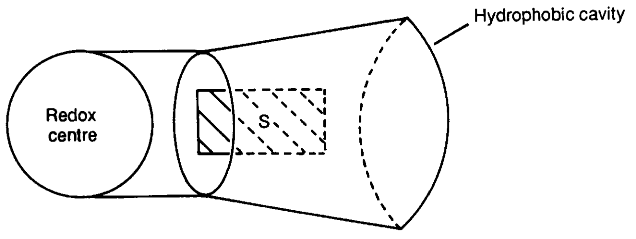
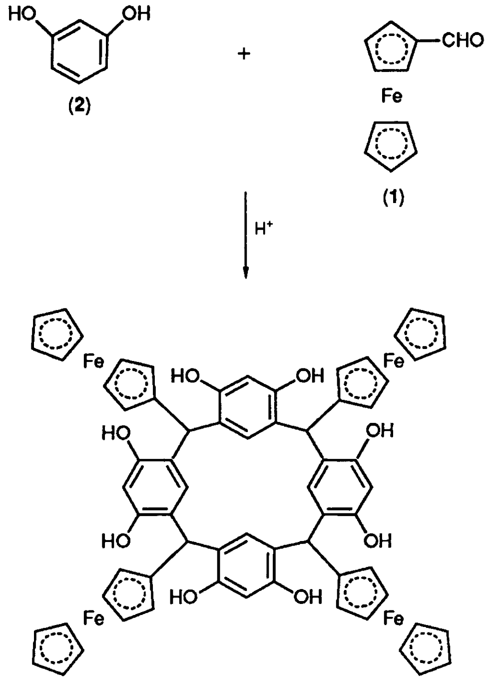


Figure 1. Simple concept of electrochemical recognition: the binding of an organic guest (S) in close proximity to redox-active centres (*e.g.* metallocene or quinone)



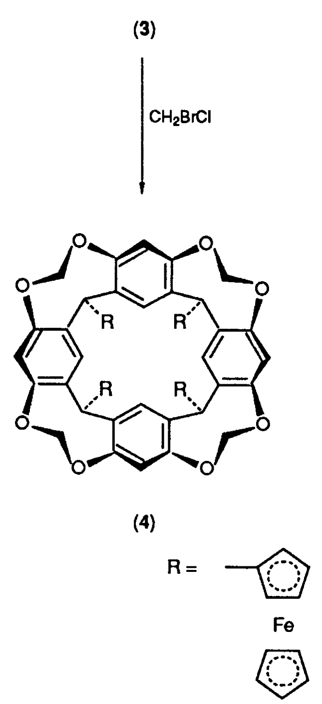
(3)

Scheme 1.

for several reasons. Its functional group derivatised chemistry is well established;[13] ferrocene itself is electrochemically well behaved in most common solvents, undergoing a reversible one-electron oxidation and is often used as an internal standard for electrochemical measurements.[14] Indeed we[15] and others[16] have recently prepared ferrocenyl crown ether, bis(crown ether), and cryptand receptors and shown these redox-active ionophores to be amperometrically redox responsive to the binding of Group 1A and 2A metal and ammonium[17] cationic guests.

In addition, the potential of hydrophobic host molecules incorporating ferrocene moieties[18,19] to act as catalysts can be inferred from the following literature reports. The chlorination of 4-chlorotoluene using chlorine gas[20] and the oxidation of butyraldehyde using oxygen gas[21] have been shown to be catalysed by the presence of ferrocene which acts as a Lewis acid in each case. Alternatively, ferrocenium hexafluorophosphate has been reported to function as a Lewis-acid catalyst for some Diels–Alder reactions.[22]

This paper describes the preparation, *X*-ray crystal-structure, molecular mechanics calculations, and electrochemical properties of, to our knowledge, the first examples of redox-active cavitand host molecules. A preliminary report of this work has been published.[23]



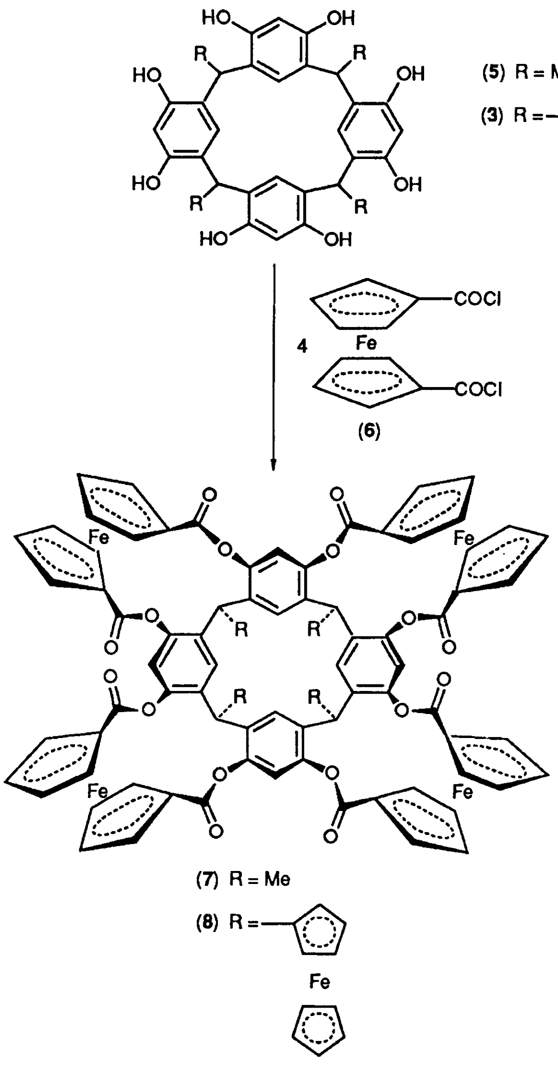
Scheme 2.

Results and Discussion

Syntheses.—The reaction of ferrocenecarbaldehyde (**1**) and 1,3-dihydroxybenzene (**2**) in the presence of hydrochloric acid and ethanol gave a black precipitate insoluble in all common organic solvents and tentatively assigned as the phenolic macrocycle (**3**) (Scheme 1). Attempts to solubilise the compound into basic media using sodium hydroxide solutions also failed. Adapting Cram's methodology[8] the treatment of a slurry of compound (**3**) in dimethylformamide (dmf) with bromochloromethane in the presence of potassium carbonate gave a crude product which was purified by column chromatography to give the redox-active cavitand (**4**) in an overall yield of 2% (Scheme 2). Octols (**3**) and (**5**)[4] suspended in dry tetrahydrofuran (thf) were condensed with 1,1′-bis(chlorocarbonyl)ferrocene (**6**)[24] in the presence of triethylamine and 4-dimethylaminopyridine resulting in the formation of redox-active cavitands (**7**) and (**8**) with the ferrocene moieties lining the wall of the cavitand cavity in 4 and 2% overall yields respectively (Scheme 3).

The structures of the cavitands were characterised by i.r., ^{1}H, and ^{13}C n.m.r. spectroscopy, fast atom bombardment mass spectrometry, and elemental analyses (see Experimental section). The simplicity of the solution ^{1}H and ^{13}C n.m.r. spectra indicated that these molecules have a C_4 rotation axis through the centre of their respective cavities. As predicted from Corey–Pauling–Koltun (C.P.K.) molecular models, variable-temperature n.m.r. studies revealed all three cavitands to be rigid over the temperature range −50 to +110 °C.

Single-crystal X-*Ray Structure of the Redox-active Cavitand* (**4**)*–Dichloromethane Inclusion Complex.*—Slow evaporation of a dilute dichloromethane–diethyl ether solution of compound (**4**) gave orange crystals suitable for analysis by *X*-ray crystallography. The asymmetric unit contains a discrete molecule of (**4**) (shown in Figures 2 and 3) together with 2.5 molecules of dichloromethane. The cavitand has a regular cone shape with approximate C_4 symmetry. The top rim of the cone can be defined by the eight oxygen atoms (plane 1 in Table 2) and the bottom rim by the four carbon atoms that bridge the



Scheme 3.

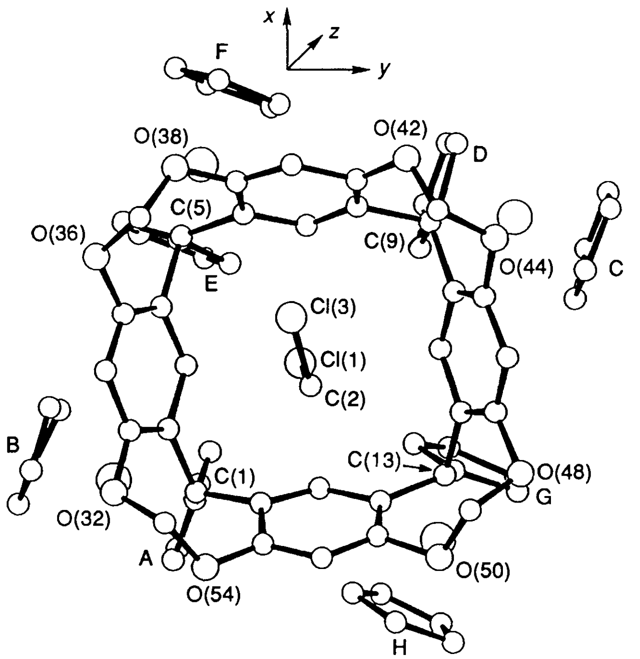


Figure 2. A view down the cone axis of the cavitand (**4**) together with the dichloromethane solvent molecule in the crystal structure

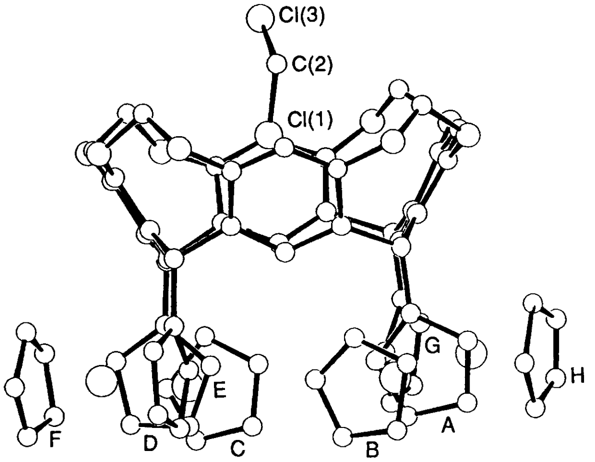


Figure 3. A view perpendicular to the cone axis of the cavitand (**4**) showing the position of the dichloromethane solvent molecule in the crystal structure

benzene rings (plane 2 in Table 2). These two planes are approximately parallel (angle of intersection 1.0°). The four benzene rings are all tilted at similar angles from these two planes making angles of intersection between 58 and 62°. The four iron cyclopentadiene groups have the expected geometry with Fe–C distances ranging from 1.969 to 2.086 Å.

The solvent molecule with full occupancy occupies a position within the cavitand (Figures 2 and 3). The four-fold symmetry of the cavitand allows us to define an orthogonal co-ordinate system which is illustrated in Figure 3. Thus z is coincident with the four-fold axis and x and y are contained within planes 7 and 8 respectively. The origin in the z direction is defined as the bottom rim of the cone, where the axis is intersected by plane 2. The top rim of the cone as defined by the eight oxygen atoms (making up plane 1) is 2.42 Å above this plane. In the X-ray crystal structure the chlorine atom is 2.58 Å above the origin (so very close to the midpoint of the eight oxygen atoms, see Figure 3) and the C–Cl bond makes an angle of 7° to the z axis. We demonstrate below by molecular mechanics that this position of the solvent molecule is one of the energy-minimum positions. The other three solvent molecules all with half occupancy are situated between molecules and do not enter the cavity.

Molecular Mechanics Calculations.—We wished to test the possibility of fitting different solvent molecules dichloromethane, carbon dioxide, and toluene into the cavitand and of investigating the positions of minimum energy. For these calculations we used a combination of molecular graphics and molecular mechanics using the CHEMMOD system.[25] The solvent molecule was placed within the cavity at a particular position and orientation and the energy of interaction with the cavitand was then minimised. The cavitand molecule is relatively rigid and its position was therefore kept fixed in the calculations. Molecular mechanics parameters were taken from the CHEMMIN[25] program for the solvent molecules and for van der Waals interactions between the solvent and cavitand. We considered the possibility of using charges on the atoms in the calculation but as test runs showed that their introduction made little difference to the results and in view of the difficulty of establishing charges in the cavitand *via* quantum mechanics (the usual method employed in the calculations of host–guest interactions[26]), because of the size of the host, charges were set at zero. This is also justified because of the nature of the

Table 1. Atomic co-ordinates ($\times 10^4$) with estimated standard deviations (e.s.d.s) in parentheses for compound (**4**)

Atom	x	y	z	Atom	x	y	z
Fe(1)	9 407(1)	2 052(2)	1 054(1)	C(5)	10 307(10)	6 228(12)	942(5)
Fe(2)	12 382(1)	5 823(2)	3 512(1)	C(6)	10 462(8)	7 112(12)	1 325(5)
Fe(3)	11 948(1)	5 580(2)	1 110(1)	C(7)	10 796(8)	6 831(13)	1 855(5)
Fe(4)	9 705(1)	2 811(2)	3 451(1)	C(8)	10 948(9)	7 607(13)	2 209(6)
C(1A)	8 706(10)	1 895(17)	1 448(6)	C(9)	11 256(8)	7 311(14)	2 779(5)
C(2A)	9.275(10)	1 208(14)	1 628(7)	C(10)	10 568(8)	7 224(12)	2 961(5)
C(3A)	9 922(11)	1 822(17)	1 788(7)	C(11)	10 247(8)	6 311(14)	2 988(5)
C(4A)	9 729(10)	2 856(15)	1 708(6)	C(12)	9 678(9)	6 225(13)	3 148(5)
C(5A)	8 979(7)	2 947(10)	1 479(5)	C(13)	9 292(8)	5 163(12)	3 151(5)
C(1B)	10 111(15)	1 732(19)	671(10)	C(14)	8 700(9)	4 914(14)	2 629(6)
C(2B)	9 560(20)	1 031(16)	529(8)	C(15)	8 874(9)	4 473(12)	2 249(5)
C(3B)	8 841(17)	1 761(21)	311(11)	C(16)	8 290(9)	4 376(12)	1 778(6)
C(4B)	9 111(15)	2 655(34)	360(9)	C(31)	7 021(9)	5 280(15)	917(7)
C(5B)	9 865(15)	2 724(22)	568(8)	O(32)	7 378(6)	4 921(9)	580(4)
C(1C)	12 890(11)	6 408(24)	4 193(7)	C(33)	8 119(10)	5 335(16)	711(6)
C(2C)	13 058(15)	5 364(28)	4 199(8)	C(34)	8 274(9)	6 086(14)	458(6)
C(3C)	12 393(13)	4 478(16)	4 067(7)	C(35)	8 942(8)	6 442(13)	524(5)
C(4C)	11 810(13)	5 556(23)	3 997(8)	O(36)	9 081(6)	7 232(9)	251(4)
C(5C)	12 115(14)	6 572(26)	4 051(9)	C(37)	9 232(10)	8 262(15)	470(6)
C(1D)	12 400(10)	4 928(17)	2 900(6)	O(38)	10 008(7)	8 366(10)	699(4)
C(2D)	12 914(10)	5 718(13)	2 990(6)	C(39)	10 302(10)	8 147(16)	1 200(7)
C(3D)	12 562(8)	6 706(12)	2 971(5)	C(40)	10 447(10)	8 947(16)	1 565(7)
C(4D)	11 787(9)	6 495(15)	2 847(5)	C(41)	10 761(8)	8 618(12)	2 051(5)
C(5D)	11 705(9)	5 428(13)	2 796(6)	O(42)	10 904(6)	9 466(8)	2 391(4)
C(1E)	10 854(8)	5 377(13)	993(6)	C(43)	10 410(10)	9 668(14)	2 666(6)
C(2E)	11 028(8)	5 065(12)	561(6)	O(44)	10 602(6)	9 027(9)	3 123(4)
C(3E)	11 548(8)	4 240(10)	732(5)	C(45)	10 272(9)	8 146(12)	3 115(5)
C(4E)	11 702(10)	4 105(18)	1 247(7)	C(46)	9 671(11)	8 015(15)	3 241(6)
C(5E)	11 278(8)	4 842(12)	1 407(6)	C(47)	9 324(12)	7 040(16)	3 260(7)
C(1F)	12 879(12)	5 999(17)	1 624(10)	O(48)	8 722(6)	7 051(8)	3 411(4)
C(2F)	13 036(15)	5 796(28)	1 189(13)	C(49)	8 051(9)	6 897(14)	3 028(6)
C(3F)	12 589(12)	6 375(16)	833(8)	O(50)	7 857(6)	5 830(10)	2 951(4)
C(4F)	12 173(12)	7 063(19)	1 020(10)	C(51)	8 013(10)	5 329(15)	2 549(7)
C(5F)	12 401(11)	6 846(15)	1 537(8)	C(52)	7 457(9)	5 209(15)	2 105(6)
C(1G)	9 843(9)	4 294(18)	3 329(7)	C(53)	7 607(8)	4 681(13)	1 741(5)
C(2G)	10 113(10)	4 076(14)	3 866(7)	O(54)	7 028(6)	4 512(9)	1 282(4)
C(3G)	10 670(10)	3 351(15)	3 948(8)	Cl(1A)	6 048(4)	2 213(6)	3 173(3)
C(4G)	10 778(11)	3 169(15)	3 505(8)	C(2A)	6 797(13)	2 907(20)	3 440(9)
C(5G)	10 263(9)	3 691(11)	3 132(6)	Cl(3A)	6 813(4)	3 939(6)	3 024(3)
C(1H)	9 333(14)	1 645(19)	3 765(9)	Cl(1B)	5 425(8)	1 812(13)	307(6)
C(2H)	9 522(12)	1 270(18)	3 365(9)	C(2B)	6 053(22)	2 920(37)	259(21)
C(3H)	9 080(14)	1 748(19)	2 941(8)	Cl(3B)	6 865(9)	2 263(14)	322(6)
C(4H)	8 631(12)	2 531(18)	3 061(8)	Cl(1C)	11 184(10)	7 897(16)	4 790(7)
C(5H)	8 778(14)	2 319(19)	3 565(12)	C(2C)	10 902(29)	9 097(43)	4 437(22)
C(1)	8 487(8)	3 888(12)	1 345(6)	Cl(3C)	10 122(10)	9 307(15)	4 598(7)
C(2)	8 684(9)	4 691(15)	1 046(6)	Cl(1D)	11 997(11)	4 871(18)	5 764(8)
C(3)	9 360(9)	5 099(12)	1 109(6)	C(2D)	12 475(31)	5 764(41)	5 532(26)
C(4)	9 549(7)	5 921(12)	873(5)	Cl(3D)	11 725(11)	6 751(16)	5 320(8)

problem; calculations of host–guest interactions where charges are necessary have been carried out on systems where there is a wide range of possible positions open to the guest within the host. Here there is only a narrow range of positions and van der Waals interactions dominate the calculations.

The positions of the solvent molecules are described relative to the co-ordinate system illustrated in Figure 3 and defined above. Dichloromethane was included with one C–Cl bond parallel to the z axis with the Cl atom inserted within the cavity and the other C–Cl bond in the xz plane. Calculations were then carried out with the molecule shifted by 0.5-Å increments along the z axis. For each position the steric energy was then minimised by adjusting the position of the solvent relative to the fixed host. In Figure 4, the steric energy is plotted against the minimised position of the leading chlorine atom within the cavity. When the chlorine atom was initially placed at a z co-ordinate of less than 1.8 Å the resulting minimisation pushed the solvent back out of the cavity. Points on the graph below this value were therefore obtained by fixing the position of the dichloromethane. Clearly this value of 1.8 Å represents the lowest position within the cavity that can be occupied without severe van der Waals repulsion. At the minimum-energy position the leading chlorine atom is *ca.* 2.60 Å from the origin. We then repeated the calculations with the dichloromethane in two further orientations obtained by rotating the molecule by 22.5 and 45° in the xy plane around the C–Cl axial bond but the curves obtained were identical to that shown in Figure 4. In all cases the solvent position adjusted during the minimisation by being slightly tilted from the z axis and rotated in the xy plane so that the final angle was *ca.* 40° from the xz plane. Calculations show that this displacement away from the axis allows the solvent to penetrate significantly further within the cavity than is possible when the C–Cl bond of the solvent molecule is restricted to the axis.

Next carbon dioxide was inserted at positions along the z axis in a similar fashion. The resulting curve (Figure 4) has a

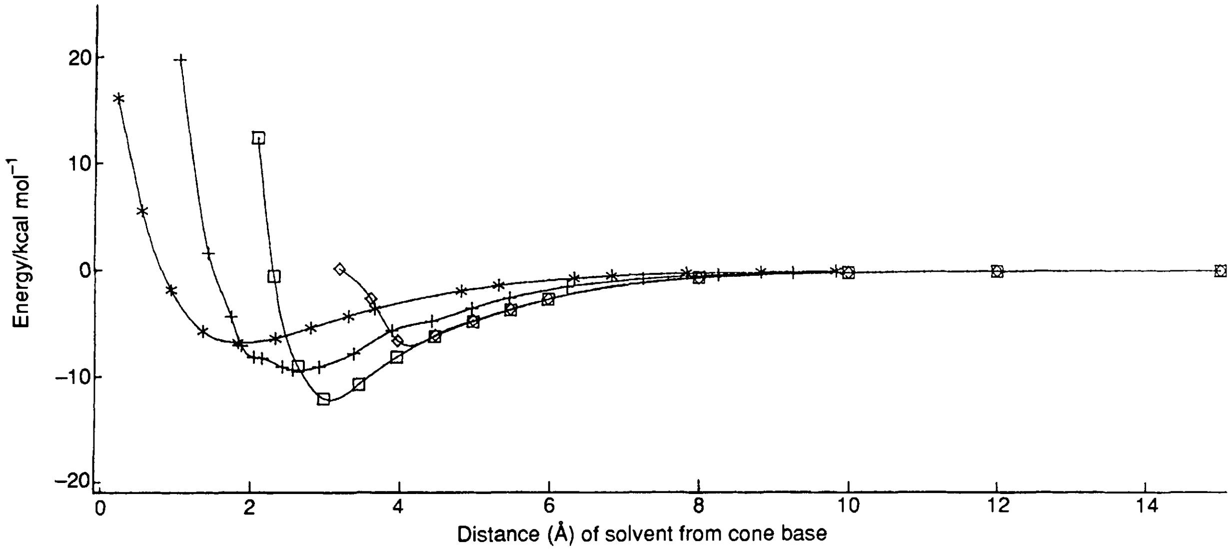


Figure 4. Plots of the distance of the leading atom (O in CO_2, Cl in CH_2Cl_2, methyl C in toluene) in the solvent molecule from the base of the cone against steric energy after minimisation *via* molecular mechanics. The graphs have been scaled by setting the sum of the energy of the host and guest when isolated to 0 kcal mol^{-1}. (✱), Carbon dioxide; (+), dichloromethane; (☐), toluene at 0° rotation; (◇), toluene at 45° rotation

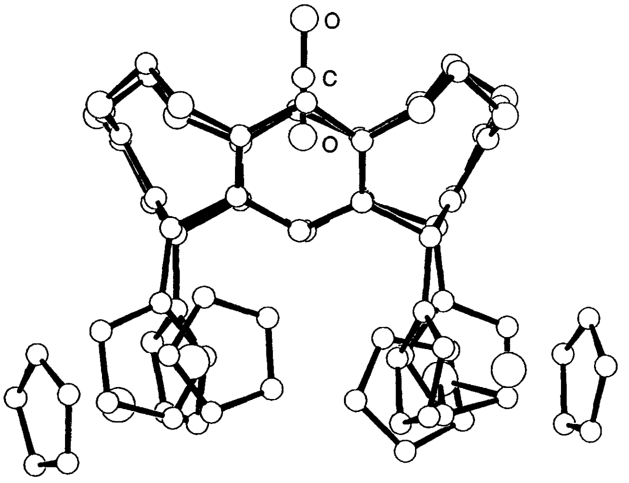


Figure 5. The minimum-energy position of CO_2 within the cavitand (**4**) as calculated by molecular mechanics

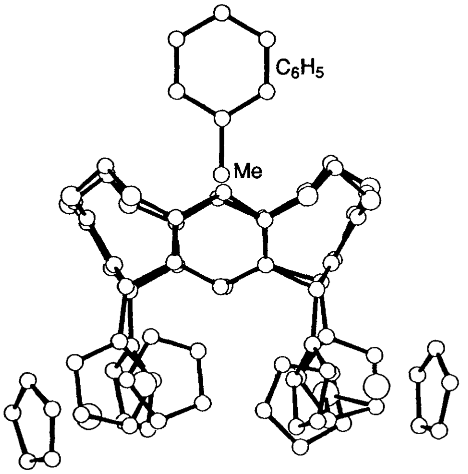


Figure 6. The minimum-energy position of toluene within the cavitand (**4**) as calculated by molecular mechanics

minimum position for the leading oxygen atom at 1.9 Å, much less than that observed for dichloromethane. It was also found that the leading oxygen atom could proceed to *ca.* 1.0 Å of the bottom of the cone before the interaction energy became positive, *i.e.* greater than for the two molecules apart. While the minimum-energy position of the carbon dioxide molecule was located with the molecule on the four-fold axis, the molecule could be moved off that axis by up to 0.25 Å without appreciable increase in steric energy. We also tested whether the carbon dioxide molecule could be located beyond the bottom of the cone but found no suitable positions in the area of the ferrocenes, particularly as the minimum distance between hydrogen atoms from cyclopentadienes is only 3.2 Å across the four-fold axis. The energy-minimum position for the CO_2 molecule within the cavity is shown as in Figure 5.

Toluene was inserted vertically with the methyl group downwards in the cavity.[27] Two sets of calculations were carried out with the benzene ring in the *xz* plane (defined as 0°) (*i.e.* stacked with aromatic rings of host) and then with the molecule rotated by 45° around the *z* axis. We did not include different positions for the methyl hydrogen atoms as they could rotate during the minimisation. Calculations were then carried out in a similar fashion at 0.5 Å intervals in *z*. At the 0° rotation the lowest-energy position for the methyl carbon atom was found to be at 3.0 Å in *z*. However at the 45° rotation the lowest-energy position was further removed at 4.0 Å in *z* (Figure 4) with a minimum energy which was 5.5 kcal mol^{-1} larger. Thus the actual position of the benzene ring is crucial to the insertion of the molecule within the cavitand. The minimum-energy position is shown in Figure 6. There have been only slight changes in position during minimisation consisting of a rotation of *ca.* 4° of the aromatic ring of the toluene guest around the *z* axis.

The validity of the molecular mechanics calculations is demonstrated by the fact that the position of the dichloromethane molecule found in the crystal structure is compatible with that predicted by the theoretical calculations. Calculations with other solvents gave useful information as to the likely positions of solvent molecules within the host cavitand. It is clear that the cavity is only large enough to allow a single atom to penetrate within it but even a small molecule such as CO_2 was not able to penetrate through to closer than 1.0 Å from the

Table 2. Least-squares planes with deviations of atoms in Å

Plane	
1	O(32) −0.09, O(36) 0.12, O(38) 0.07, O(42) −0.05, O(44) −0.16, O(48) 0.17, O(50) 0.06, O(54) −0.11
2	C(1) −0.09, C(5) 0.09, C(9) −0.09, C(13) 0.09
3	C(2) −0.04, C(3) 0.01, C(4) 0.01, C(33) 0.05, C(34) −0.03, C(35) −0.00
4	C(6) −0.04, C(7) 0.01, C(8) 0.01, O(38) 0.05, C(39) −0.01, C(40) −0.01
5	C(11) −0.03, C(12) 0.04, C(13) 0.01, O(44) 0.04, C(45) −0.02, C(46) −0.03
6	C(14) −0.04, C(15) 0.02, C(16) 0.01, O(50) 0.02, C(51) 0.02, C(52) −0.02
7	C(7) −0.05, C(15) 0.05, C(40) 0.03, C(52) −0.03
8	C(3) 0.26, C(11) −0.24, C(35) 0.18, C(46) −0.17

Angles (°) between planes: 1 and 2, 1.0; 1 and 3, 61.6; 1 and 4, 60.4; 1 and 5, 61.1; 1 and 6, 59.3; 7 and 8, 89.0°; 1 and 7, 89.7; 1 and 8, 89.8. The latter two planes are approximately parallel (angle of intersection 1.0°).

Table 3. Electrochemical data *

Compound	E_{Pa}/V	E_{Pc}/V
(4)	+0.63	+0.55
(7)	+1.15	+1.07
Ferrocene	+0.60	+0.52

* Obtained from dichloromethane solutions which were 1 × 10^{-3} mol dm^{-3} in each compound and 0.2 mol dm^{-3} in $[NBu_4][BF_4]$. Values are quoted with reference to the s.c.e.

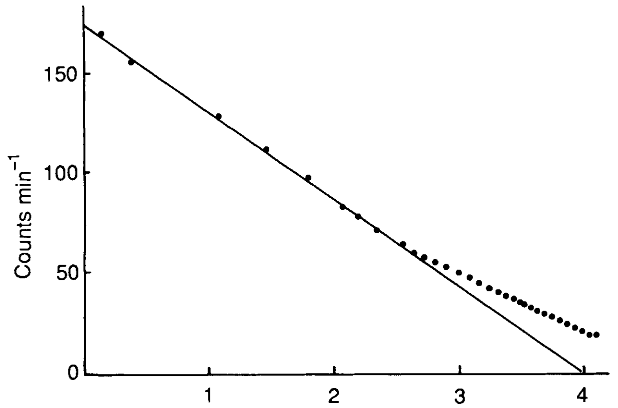
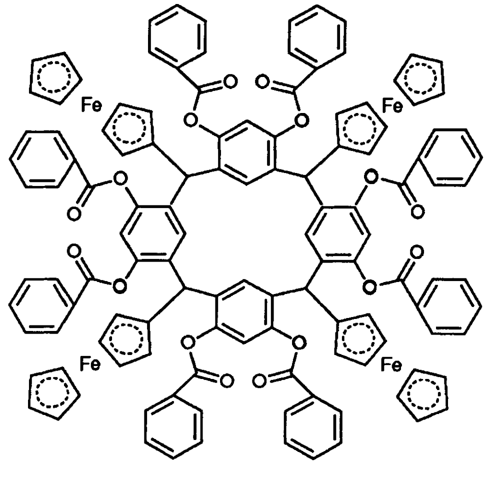


Figure 7. Plot of Δcounts/Δtime *versus* charge passed for compound (**4**). Conditions: 0.2 mol dm^{-3} $[NBu_4][BF_4]$ in CH_2Cl_2; c.p.e. at 1.0 V *versus* s.c.e.

bottom of the cone. With a bulkier atom (*e.g.* Cl in CH_2Cl_2) or a methyl group (as in toluene) the allowed penetration is far less. Indeed toluene in an unfavourable rotation cannot penetrate further than 4.0 Å from the bottom of the cone. It is therefore clear that an increase in the cavity size is required before more complete inclusion of these and larger guest molecules can be achieved.

Electrochemical Studies.—The electrochemical properties of compounds (**4**) and (**7**) were studied by cyclic voltammetry. The E_{Pa} and E_{Pc} values for the respective single oxidation waves observed for both are reported in Table 3. A controlled-potential electrolysis (c.p.e.) of (**4**) was carried out in dichloromethane (1.0 V *versus* saturated calomel electrode, s.c.e.). The plot of Δ(counts)/Δ(time) *versus* charge passed confirmed that the single oxidation wave represented a four-electron process (Figure 7). The four ferrocenyl units of compound (**4**) are therefore electronically equivalent and undergo independent reversible one-electron transfers at the same potential in dichloromethane. Interestingly this result is in contrast to that for the related macrocycle (**9**) which exhibits two two-electron reversible oxidation waves.[28] Detrimental electrode coating thwarted attempts to repeat analogous c.p.e. experiments with compound (**7**), however by comparison with (**4**) it is likely that the respective four ferrocenoyl units are all oxidised at the same potential.*



(9)

Electrochemical Inclusion-complexation Studies.—An examination of a C.P.K. model of compound (**7**) indicated the four disubstituted ferrocenoyl groups within this molecule formed an upper rim on the small hydrophobic cavity created by the basic macrocyclic arene structure. These four redox-active centres are thus in close proximity to any guest included inside this cavity. The molecular mechanics calculations carried out on host–guest complexes formed with (**4**) suggested that such a guest would be required to be small, for example carbon dioxide. Consequently the effect of bubbling carbon dioxide through, or adding dichloromethane to, a dimethylformamide (dmf) solution of (**7**) was studied by cyclic voltammetry.

These investigations were carried out in dmf in the hope that the relatively polar nature of this solvent would encourage the less-polar guests to enter the hydrophobic cavity of compound (**7**). Unfortunately the cyclic voltammogram of (**7**) alone in dmf exhibited an irreversible wave (E_{Pa} = +1.06 V). Nonetheless the effect of bubbling carbon dioxide for at least 10 min through or adding up to eight equivalents of dichloromethane to the electrochemical solution of (**7**) in dmf was investigated. Very small anodic shifts ($\Delta E_{Pa} \leqslant 10$ mV) were observed which, within experimental error, are insignificant. There are several possible explanations for the absence of any significant change in the electrochemical behaviour of (**7**) upon addition of either guest. First, the molecular mechanics calculations performed on host–guest complexes of compound (**4**) with carbon dioxide and dichloromethane indicated that these guests cannot penetrate very deeply into the cavity of this host, and by analogy the guests may be unable to be included in sufficient close proximity to the redox-active moieties of (**7**). Secondly, the complexation of one of these *neutral* guest species near the redox-active centres

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* The electrochemical properties of compound (**8**) are complicated and are currently under investigation.

in an organic solvent is unlikely to perturb the electron density at the ferrocene iron atom to anything like the same extent as complexation of *charged* guests such as Group 1A, 2A metal and ammonium cations.[15–17]

Conclusion

Novel redox-active cavitand host molecules containing multiple ferrocenyl redox centres have been prepared. These compounds have been shown to undergo independent reversible one-electron oxidations in dichloromethane. The addition of possible guest species, carbon dioxide and dichloromethane, however, caused no significant perturbation in the electrochemical behaviour, albeit irreversible of compound (**7**) in dmf. This is not perhaps surprising, especially in view of molecular mechanics calculations performed on complexes with the similar cavitand (**4**) which indicated the dimensions of the cavity of this molecule would only allow partial inclusion of carbon dioxide and dichloromethane guest species. The future design and synthesis of an expanded basic macrocyclic arene structure from which to construct novel redox-active host molecules capable of including larger organic molecular species in solution may be desirable. Furthermore, the incorporation of functional groups such as sulphonate or ammonium into these redox-active molecules, with the aim of producing water-soluble electroactive hosts, may encourage the subsequent inclusion of neutral guest species through the hydrophobic effect.[29]

Experimental

Solvent and Reagent Pre-treatment.—Where necessary, solvents were purified by distillation prior to use. The following drying agents and conditions were used before distillation: acetonitrile was distilled from CaH_2, dichloromethane from P_2O_5, hexane and diethyl ether from sodium, toluene and thf from sodium using benzophenone as the indicator, dmf under reduced pressure from $MgSO_4$, and thionyl chloride from triphenyl phosphite.

Unless otherwise stated, commercial grade chemicals were used without further purification. The octol (**5**)[4] and 1,1′-bis(chlorocarbonyl)ferrocene (**6**)[24] were prepared according to the literature procedures.

Instrumental Methods.—Melting points were recorded on a Gallenkamp apparatus in open capillaries and are uncorrected. Literature values of known compounds are quoted in parentheses. Infra-red spectra were obtained on a Perkin-Elmer 297 instrument (4 000—600 cm^{-1}) as KBr discs, n.m.r. spectra on JEOL FX-90Q, GX-270 and Bruker WH400 instruments using tetramethylsilane as internal standard. Mass spectra and fast atom bombardment spectra were recorded on a Kratos MS80 RF mass spectrometer; the latter used an argon primary beam and 3-nitrobenzyl alcohol as the matrix. The u.v.–visible spectra were recorded on a Shimadzu uv-24- spectrophotometer. All elemental analyses were performed at the University of Birmingham.

Electrochemical Measurements.—Cyclic voltammetry, differential pulse voltammetry, and controlled-potential electrolysis were carried out with a PAR 174A potentiostat. All the electrochemical measurements were performed under nitrogen, and used $[NBu^n{}_4][BF_4]$ as the supporting electrolyte.

The cyclic voltammetry and differential-pulse voltammetry measurements were carried out using a three-electrode cell, which incorporated a s.c.e. as reference electrode, a platinum-wire auxiliary electrode, and a platinum-bead working electrode. The current–voltage curves were recorded with a Philips X-Y recorder.

During the controlled-potential electrolysis a large platinum-gauze electrode was placed in the main cell compartment containing the stirred test solution. The counter electrode was another large platinum-gauze square, held in a secondary cell compartment isolated by a sintered-glass disc. The current passed was measured using a Hi-tek electronic integrator, which was calibrated in conjunction with the cell using a known amount of ferrocene.

Syntheses.—2,8,14,20-*Tetraferrocenylpentacyclo*-[19.3.1.$1^{3,7}$.$1^{9,13}$.$1^{15,19}$]*octacosa*-1[25],3,5,7[28],9,11,13[27],15,17,19(26),21,23-*dodecaen*-4,6,10,12,16,18,22,24-*octol* (**3**). 1,3-Dihydroxybenzene (**2**) (2.2 g, 20 mmol) and ferrocenecarbaldehyde (**1**) (4.2 g, 20 mmol) were added to 95% ethanol in water (16 cm^3). To this stirred slurry was added slowly 11.8 mol dm^{-3} hydrochloric acid (4 cm^3), during which time a black precipitate rapidly formed. The reaction mixture was stirred at 75 °C for 4 h, and then cooled to 0 °C. The black precipitate was filtered off, washed with water until the washings were no longer acidic, and finally dried under vacuum to give compound (**3**) (6.12 g), m.p. >250 °C, i.r. 3 700—2 600 cm^{-1} (hydrogen-bonded OH). This material was used without further purification in subsequent reactions.

1,21,23,25-*Tetraferrocenyl*-2,20:3,19-*dimetheno*-1H,23H,25H-*bis*[1,3]*dioxocino*[5,4-i : 5′,4′-i′]*benzo*-[1,2-d:5,4-d′]*bis*[1,3]*benzodioxocin* (**4**). To a mixture of compound (**3**) (6.12 g, 5 mmol) and of anhydrous potassium carbonate (8.00 g, 58 mmol) in dmf (150 cm^3) was added bromochloromethane (4.00 g, 31 mmol). This slurry was stirred under nitrogen at 85 °C for 68 h. The mixture was rotary evaporated to dryness, and the residue triturated in dichloromethane (100 cm^3). The suspension was filtered through a bed of Celite, and the bed washed thoroughly with dichloromethane (500 cm^3). The combined washings were dried over $MgSO_4$, filtered, and rotary evaporated to dryness. The residue was purified by column chromatography on alumina with dichloromethane as the mobile phase to give compound (**4**) as orange crystals (0.13 g, 2% overall yield for the preparation of the octol and subsequent reaction with bromochloromethane), m.p. >250 °C, *m/z* 1 272. N.m.r. ($CDCl_3$): ^1H, δ 3.75 (20 H, s, ferrocenyl H), 4.28 (8 H, s, ferrocenyl-H), 4.42 (8 H, s, ferrocenyl H), 4.52 (4 H, d, *J* 7.1, inner OCH_2O), 5.84 (4 H, d, *J* 7.1 Hz, outer OCH_2O), 5.96 (4 H, s, CH), 6.55 (4 H, s, aryl H), and 7.64 (4 H, s, aryl H); ^{13}C, δ 38.37 (CH), 68.32, 69.19, 70.49, 87.88 (ferrocenyl C), 99.69 (OCH_2O), 115.89, 125.09, 138.87, and 153.86 (aryl C) (Found: C, 66.9; H, 4.9. Calc. for $C_{72}H_{56}Fe_4O_8$: C, 67.9; H, 4.4%).

Cavitand (**7**). A mixture of octol (**5**) (0.081 g, 0.15 mmol), triethylamine (0.2 cm^3, 1.4 mmol), 4-dimethylaminopyridine (0.03 g, 0.25 mmol), and 1,1′-bis(chlorocarbonyl)ferrocene (**6**) (0.23 g, 0.75 mmol) in thf (100 cm^3) was stirred under nitrogen at reflux for 66 h. The orange-red solution was then rotary evaporated to dryness, and the resulting orange powder dissolved in dichloromethane. After being washed with water, this solution was dried over $MgSO_4$, filtered, rotary evaporated, and purified by column chromatography on alumina using dichloromethane–methanol (99:1, v/v) as the mobile phase. The product (**7**) was isolated as small orange crystals (0.009 g), 4% overall yield for the preparation of the octol and subsequent reaction with 1,1′-bis(chlorocarbonyl)ferrocene. M.p. >250 °C, *m/z* 1 497, i.r. 1 735 cm^{-1} (C=O stretch). N.m.r. ($CDCl_3$): ^1H, δ 1.76 (12 H, d, *J* 7.3, CH_3), 4.58, 4.61 (16 H, 2 × s, ferrocenyl H), 4.88 (8 H, s, ferrocenyl H), 4.98 (8 H, s, ferrocenyl H), 5.10 (4 H, q, *J* 7.3 Hz, CH), and 7.62 (8 H, br s, aryl H); ^{13}C, δ 23.41 (CH_3), 29.85 (CH), 72.09, 72.61, 72.83, 73.00, 73.68, (ferrocenyl C), 116.28, 125.84, 133.48, 146.58 (aryl C), and 168.66 (C=O) (Found: C, 64.1; H, 4.1. Calc. for $C_{80}H_{56}Fe_4O_{16}$: C, 64.2; H, 3.8%).

Cavitand (**8**). The procedure followed for the preparation of compound (**8**) was that described for (**7**), using octol (**3**), except that the reflux time was reduced from 66 to 40 h. The product was purified by column chromatography on alumina with dichloromethane–methanol (99:1, v/v) as the eluant to give (**8**) as an orange powder (0.005 g, 2% overall yield), m.p. >250 °C, *m/z* 2 177, i.r. 1 730 cm^{-1} (C=O stretch). N.m.r. ($CDCl_3$): ^{1}H, δ 3.99 (20 H, s, ferrocenyl H), 4.11, 4.14 (16 H, 2 × s, ferrocenyl H), 4.95 (16 H, s, ferrocenyl H), 4.99 (8 H, s, ferrocenyl H), 5.08 (8 H, s, ferrocenyl H), 5.89 (4 H, s, CH), 7.26 (4 H, s, aryl H), and 7.29 (4 H, s, aryl H); ^{13}C, δ 29.72 (CH), 67.99, 68.32, 68.61, 69.75, 70.10, 71.60, 72.12, 72.93, 73.91 (ferrocenyl C), 91.79 (ferrocenyl C, *ipso*), 115.57, 130.62, 131.69, 146.45 (aryl C), and 168.63 (C=O) (Found: C, 63.0; H, 3.3. Calc. for $C_{116}H_{80}Fe_8O_{16}$: C, 64.0; H, 3.7%).

Crystallography for Compound (**4**).—*Crystal data.* $C_{72}H_{56}Fe_4O_8\cdot2.5CH_2Cl_2$, $M = 2\,936.2$, monoclinic, space group $P2_1/n$, $a = 19.336(23)$, $b = 12.812(11)$, $c = 28.280(25)$ Å, $\beta = 108.7(1)°$, $U = 6\,645.6$ Å^3, $F(000) = 3\,012$, $D_m = 1.51$ g cm^{-3}, $Z = 4$, $D_c = 1.47$ g cm^{-3}, Mo-K_α radiation ($\lambda = 0.7107$ Å), μ(Mo-K_α) = 11.3 cm^{-1}.

An irregularly shaped crystal of approximate size 0.5 × 0.3 × 0.3 mm was grown by slow evaporation in dichloromethane–diethyl ether, then taken out of solution and immediately sprayed with lacquer and placed within a capillary tube together with a small amount of solvent. Preliminary examination was carried out on a precession camera. The crystal was then mounted upon a STOE-2 diffractometer to rotate around the *b* axis. 10 968 Independent reflections were measured with a 2θ maximum of 50°. Background counts were for 20 s and a scan rate of 0.0333° s^{-1} was applied to a width of $(1.5 + \sin\mu/\tan\theta)$. No decay in intensity was observed for the standard reflections. 3 873 Reflections with $I > 2\sigma(I)$ were used in subsequent calculations. The positions of the four iron atoms were determined by direct methods and the remaining atoms in the molecule were located by successive cycles of Fourier difference syntheses and least-squares refinement. All non-hydrogen atoms in the molecule were given anisotropic thermal parameters. Hydrogen atoms were then included in calculated positions. A common refined thermal parameter was given to each set of hydrogen atoms in a cyclopentadienyl ring and an additional parameter to hydrogen atoms in the cavitand. Four molecules of dichloromethane were then also located; one molecule was given full occupancy and the other three half-occupancy. All four solvent molecules were refined with isotropic thermal parameters, with common C–Cl and Cl · · · Cl distances. Hydrogen atoms were not included in the solvent molecules.

Calculations were performed using full-matrix least-squares methods with a weighting scheme $w = 1/[\sigma^2(F) + 0.003F^2]$. The SHELX 76 system[30] and some of our own programs were employed on the Amdahl V7 computer at the University of Reading, but the final refinement cycles were carried out on the Cray X-MP at the University of London Computer Centre. The final *R* value was 0.083 ($R' = 0.087$). In the final cycle of refinement no shift was $>0.1\sigma$ and there were no significant peaks in the final Fourier difference map. Positional co-ordinates are given in Table 1, least-squares planes in Table 2).

Additional material available from the Cambridge Crystallographic Data Centre comprises H-atom co-ordinates, thermal parameters, and complete bond lengths and angles.

Acknowledgements

We thank the S.E.R.C. for a C.A.S.E. award (to E. L. T.), for grants for the Molecular Graphics equipment and for the diffractometer, for use of the high-field n.m.r. service at the University of Warwick and the Mass Spectrometry Service at University College Swansea. We are grateful to Mr. A. W. Johans for his assistance with the crystallographic investigations, and the Research Corporation Trust, L. and D. Blond for additional financial support.

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Received 8*th February* 1990; *Paper* 0/00590H