

Heterocalixarenes featuring the benzimidazol-2-one subunit. Synthesis and X-ray structural studies of solvent inclusions



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The heterocalixarenes **4a,b** and **5a–f** have been synthesized. Compounds **4a,b** and **5a–d** were obtained by two-step fragment condensation from benzimidazol-2-one and 1,3-bis(bromomethyl)benzene building elements using blocking/deblocking, high dilution and template (Cs_2CO_3) techniques to give **4a/5a** and **4b/5b** in an approximate 1:2 or 1:3 ratio of the cyclo oligomers. The cleavage of the methyl ether groups of **5a** and **5b** yielded the tetraphenols **5e** and **5f**, respectively. The calix hosts **4a**, **5a–c** and **5f** form crystalline inclusion compounds with organic solvent molecules. X-Ray crystal structures of the solvent inclusions **5a**·methylene chloride (1:1), **5b**·toluene·water (1:2:1), **5c**·acetone·methylene chloride (1:1:1) and **5f**·toluene (1:3) have been studied. The molecular structures show a general trend of having enhanced calix-forming ability compared with conventional calix[8]arenes of the same ring size. The shape of the host molecules appear to be determined by the packing of the symmetry centres of related host molecules on either one of the benzimidazolone rings yielding basket-like hosts (**5a–c**) or on one of the phenol rings resulting in a chair-like host shape (**5f**), always exhibiting base-stacking characteristics between the aromatic planes concerned.

Conventional calixarenes are basket-shaped macrocyclic compounds derived from the condensation of a *para*-substituted phenol and formaldehyde.¹ In the past decade a great many structural modifications involving ring size and functionalization of the calixarene have been performed and studied in terms of conformational flexibility, hollow space effects and inclusion behaviour.² A current area of research in calixarene chemistry is the use of the calixarene framework as a module building block in order to construct highly preorganized and more complex molecular containers and complexants.³ On the other hand, calixarenes made of heterocycles instead of phenols are very rare,⁴ although they are expected to have different properties, comparable to the differences seen by the replacement of oxygen in crown compounds⁵ by a heterocyclic subunit analogue.⁶ Heterocalixarene is the obvious name for this particular class of macrocycle.

Here we report the synthesis, inclusion formation and structural behaviour of eight different compounds of this category (**4a,b**, **5a–f**), all having the benzimidazol-2-one characteristic building unit and the 1,3-phenylene component in an alternate cyclic arrangement. Individual compounds, however, differ in the ring size and substitution of the phenylene nucleus, thus allowing different rigidity, polarity and hollow shape of the molecule to be possible. A key aim of this study is to explore both the mode of correspondence and the discrepancy between calixarenes and heterocalixarenes.

Results and discussion

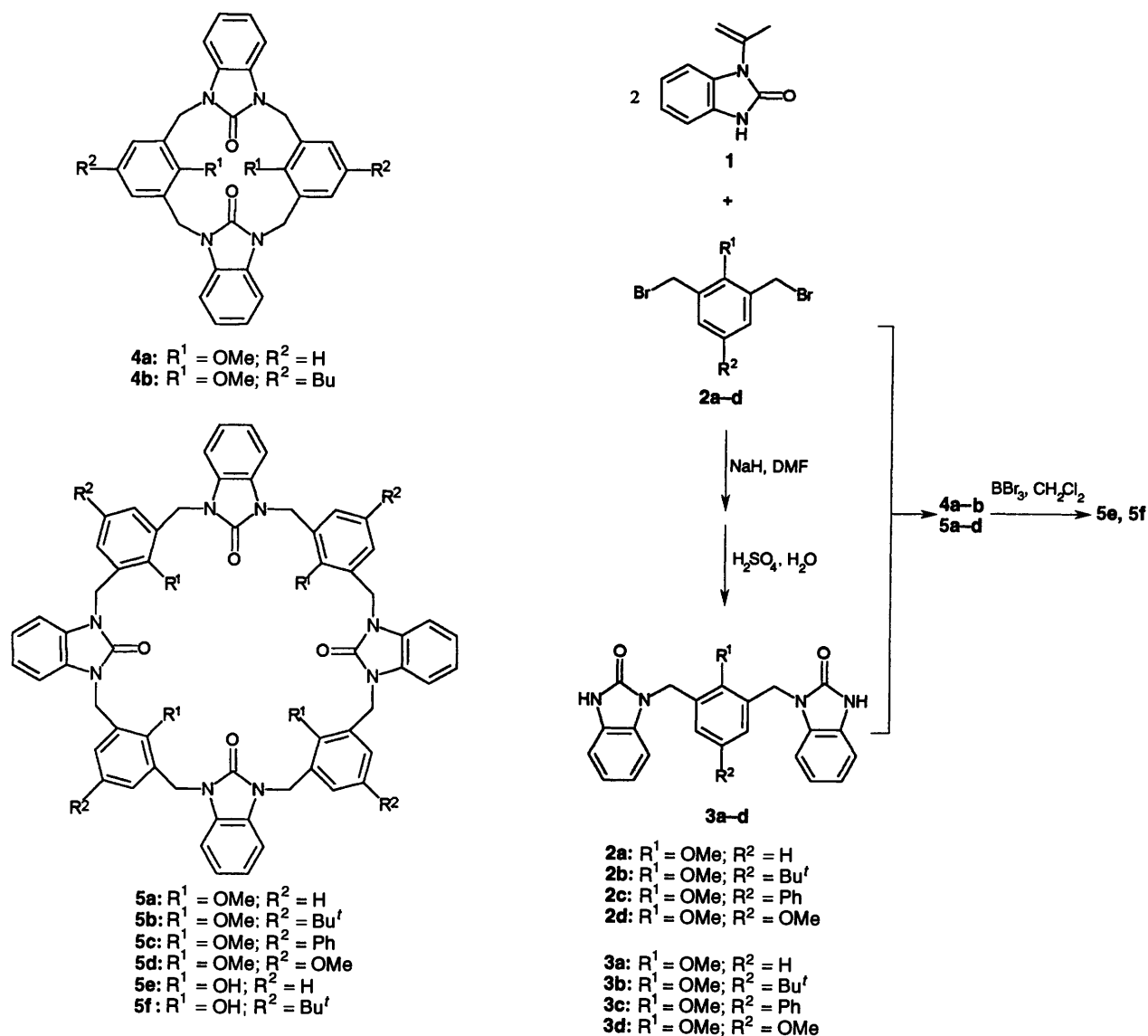
Synthesis

The general pathway for making the heterocalixarenes **4a,b**, **5a–d** is as illustrated in Scheme 1 which shows that the blocking group technique and convergent ring formation reaction are the main strategic elements of the synthesis. This involves coupling between two mono-blocked benzimidazol-2-one (**1**) and one 1,3-bis(bromomethyl)benzene (**2**) building units to yield a trinuclear fragment (**3**), which after deprotection was reacted with the above dibromide to form the calixarene macrocycles. Mixtures of two sizes (heterocalix[4]- and heterocalix[8]-arenes) were obtained for the macrocyclizations between **2a** and **3a** (**4a**, **5a**) or **2b** and **3b** (**4b**, **5b**), whereas **2c** and **3c** or **2d** and **3d** exclusively gave the heterocalix[8]arene (**5c**, **5d**), suggesting that the substituent at position 4 of the *m*-phenylene is a factor of control.

The starting *N*-propen-2-ylbenzimidazol-2-one (**1**) was synthesized from *o*-phenylene diamine and ethyl acetoacetate in high yield.⁷ The building block **2a** was obtained by bromination with *N*-bromosuccinimide (NBS) of 2,5-dimethylanisole.⁸ The bis(bromomethyl) compounds **2b–d** were prepared from the corresponding bis(hydroxymethyl) phenols^{9a} by methylation with dimethyl sulfate (DMS) and subsequent bromination with HBr in acetic acid.^{9b,c,10} Alkylation of **1** by using bromides **2** was carried out by treatment with sodium hydride in dimethylformamide (DMF).¹¹ The *N*-protecting propen-2-yl group was cleaved with cold sulfuric acid to give the components **3a–d**.

The macrocyclizations were performed under high-dilution conditions in DMF as the solvent and with Cs_2CO_3 to act as a temporary template.¹² In two cases (**5a,b**), BBR_3 mediated

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Scheme 1

cleavage of methyl groups of the methoxy substituents was effective and yielded the tetraphenols **5e** and **5f**.

The crystalline inclusion compounds were obtained by simple recrystallization of the calixarene from the respective guest solvent or slow evaporation of a calixarene solution in a solvent mixture (see Experimental section).

X-Ray structural studies

Crystallographic, experimental and model refinement data for the solvent inclusions of **5a–c** and **5f** are shown in Table 1. Atomic coordinates and tables of bond lengths and angles have been deposited with the Cambridge Crystallographic Data Centre (CCDC).[‡]

Intramolecular and intermolecular features of the inclusion compounds

5a·Dichloromethane (1:2). Heterocalixarene **5a** adopts a crystallographic two-fold axis and has an ellipsoidal shape with the methoxy and carbonyl oxygen atoms pointing away from the cavity (Fig. 1). The eight methylene bridging carbon atoms ('belt' atoms in the centre) define a medium flat main calixarene plane with a maximum deviation of 0.25 Å, approximately. The transannular distances between equivalent bridging carbon atoms indicate an oval molecular shape, with an asphericity of

2.08 Å (Table 2). The methoxyphenyl (A and C) and benzimidazole (B and D) moieties adopt alternating positions and show a helical arrangement around the macro ring with dihedral angles best approximating to right angles for the compounds reported here (Table 3). Conformation of the calixarene can also be characterized by the dihedral angles δ between the flat fragments and the mean plane of methylene bridging carbon atoms with the largest deviations for rings C and D [$\delta = 107.1(1)^\circ$ and $\delta = 139.2(1)^\circ$, cf. the mean value of $\delta = 124(2)^\circ$ for calix[4]arenes¹³].

The guest molecule lies partially inside the host macrocycle (Fig. 1) and is disordered in the cavity over three close positions with populations 1/2, 1/4 and 1/4. Since the thermal motion of guest atoms are very high one could perceive that the complex resembles a molecular cup filled with liquid. Apparently the position of the CH_2Cl_2 guest molecule is determined by the interplay of rather weak forces and steric fit. Owing to substantial freedom within the calixarene cavity, disorder and high thermal motion of the guest molecule does not allow for a better description of the host–guest contact geometry. The shortest distance for the major guest position is $\text{Cl}(1)\cdots\text{C}(21) = 3.48(1) \text{ \AA}$ (cf. Fig. 1). No other guest molecules were found in the lattice thus **5a·CH₂Cl₂** (1:2) is an *endo*-calixarene or cavitare¹⁴ complex with 1:2 host–guest stoichiometry. Two symmetry centres related benzimidazolone rings are placed in two hosts in the crystal lattice such that they partially overlap and have interplanar distances 3.4–3.6 Å.

[‡] For further details, see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 2*, 1996, Issue 1. Any request to the CCDC for this material should quote the full literature citation and the reference number 188/24.

Table 1 Crystal data and structure refinement for **5a**·dichloromethane 1:2, **5b**·toluene·water 1:2:1, **5c**·acetone·dichloromethane 1:1:1 and **5f**·toluene 1:3

Compound	5a ·2(CH ₂ Cl ₂)	5b ·2(C ₇ H ₈)·H ₂ O	5c ·CH ₂ Cl ₂ ·C ₃ H ₆ O	5f ·3(C ₇ H ₈)
Empirical formula	C ₆₆ H ₆₀ N ₈ O ₈ Cl ₄	C ₉₄ H ₁₀₆ N ₈ O ₉	C ₉₂ H ₈₀ N ₈ O ₉ Cl ₂	C ₉₇ H ₁₀₄ N ₈ O ₈
Formula weight	1235.07	1491.94	1512.61	1509.96
<i>T</i> /K	200(2)	200(2)	298(2)	200(2)
Radiation, λ/Å	1.5418	1.5418	1.5418	1.5418
Crystal system	Orthorhombic	Tetragonal	Monoclinic	Triclinic
Space group	<i>Pbcn</i>	<i>I4₁/acd</i>	<i>C2/c</i>	<i>P1</i>
<i>a</i> /Å	15.847(2)	32.333(10)	24.241(2)	11.816(3)
<i>b</i> /Å	14.375(1)	32.333(10)	16.170(1)	13.260(3)
<i>c</i> /Å	27.867(4)	33.194(14)	20.384(1)	15.702(4)
α/degrees	90	90	90	102.11(2)
β/degrees	90	90	93.42(1)	96.04(2)
γ/degrees	90	90	90	109.13(2)
<i>V</i> /Å ³	6348(1)	34 698(21)	7976(2)	2235(1)
<i>Z</i>	4	16	4	1
<i>D</i> /g cm ⁻³	1.292	1.142	1.259	1.122
<i>μ</i> /cm ⁻¹	21.9	5.7	12.50	5.7
<i>F</i> (000)	2 576	12 768	3 176	806
Crystal size/mm	0.20 × 0.25 × 0.35	0.21 × 0.20 × 0.60	0.45 × 0.42 × 0.27	0.15 × 0.25 × 0.70
θ-range data coll./degrees	3.17–76.61	2.73–77.16	3.29–75.07	2.93–76.40
Index ranges	−19 < <i>h</i> < 0, 0 < <i>k</i> < 18, 0 < <i>l</i> < 35	0 < <i>h</i> < 40, 0 < <i>k</i> < 40, 0 < <i>l</i> < 41	0 < <i>h</i> < 30, 0 < <i>k</i> < 20, −25 < <i>l</i> < 25	0 < <i>h</i> < 14, −16 < <i>k</i> < 15, −19 < <i>l</i> < 19
Reflections collected	6 687	12 013	8 353	9 681
Indep. reflect. [<i>R</i> (int)]	6 687 [0.0]	7 733 [0.051]	8 174 [0.048]	9 216 [0.035]
Data/restraints/params	6 636/9/397	7 717/267/428	7 329/0/528	7 688/1/526
Goodness-of-fit on <i>F</i> ²	1.018	1.021	1.075	1.095
Final <i>R</i> indices <i>R</i> ₁ & <i>wR</i> ² , [<i>I</i> > 2σ(<i>I</i>)]	0.0838, 0.2142	0.1270, 0.3134	0.0724, 0.2003	0.0854, 0.2307
<i>R</i> ₁ and <i>wR</i> ² indices (all data)	0.1642, 0.2776	0.2422, 0.3847	0.1024, 0.2562	0.1575, 0.3098
Large peak/hole/eÅ ⁻³	0.59/−0.52	0.40/−0.64	0.77/−0.29	0.88/−0.28

Table 2 Transannular distances across, and the maximum deviations (asphericity factors, Δ*sp*^a) from, the main least-squares plane of the bridging methylene carbon atom in **5a**, **5b** and **5c** with their esds (in Å)

Compound	Minimum (Å)	Maximum (Å)	Δ <i>sp</i> /Å	Δ/Å
5a	11.900(9)	13.979(9)	2.079	0.249(5)
5b	12.87(2)	13.39(2)	0.52	0.163(6)
5c	11.775(4)	13.898(4)	2.123	0.423(2)

^a Δ*sp* sphericity aberration parameter: Δ*sp* = *d*_{max} − *d*_{min}.

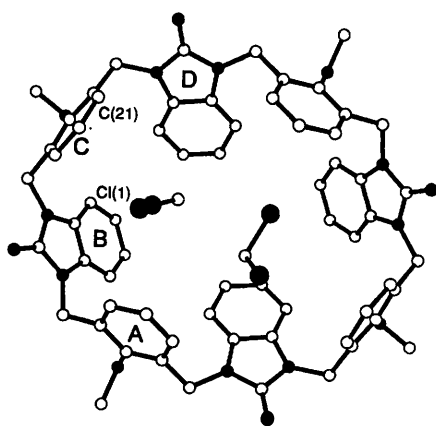


Fig. 1 Top-view of the molecular structure of **5a**·CH₂Cl₂ 1:2. Only guest locations with the two highest occupancies are shown with atom indications for the host–guest interactions.

5b·Toluene·water (1:2:1). The observed conformation in this complex is principally dictated by a two-fold crystallographic axis. The heterocalixarene **5b** has the most spherical shape (Fig. 2). The transannular distances between the two-fold related bridging carbon atoms also indicate the most globular molecular shape (0.52 Å deviation, cf. Table 3) among the structures discussed here. The deviation of the atoms forming the central plane is also the smallest. These data alone would indicate a fairly stress-free molecular conformation in contrast to **5a** and **5c** in their complex form. Arrangement of the flat frag-

ments A–D with respect to the average plane of bridging carbon atoms is such that it most closely resembles the mean value [$\delta = 124(2)^\circ$] for the cage-forming calix[4]arenes (Table 3). However, mutual arrangement of the consecutive aromatic rings A–D deviates somewhat more from a right-angles arrangement. The calixarene **5b** forms a closed cavity which completely encapsulates one toluene molecule. This toluene guest in the middle of the cavity lies close to and almost parallel with the bridging carbon atoms mean plane [guest atom distances to this plane range from 0.1(2)–0.52(2) Å, for dihedral angles cf. Table 3]. As a consequence of the two-fold crystallographic symmetry the guest molecule occupies two positions with equal probability (static disorder). To avoid the very short interatomic contacts between host and guest one of the benzimidazole moieties becomes disordered (B₁ and B₂ in Fig. 2) correlating with the toluene molecule position. Methyl groups of both of the *p*-*tert*-butyl groups are also disordered and occupy two positions related by rotations of about 34 and 23° around the corresponding C–C bonds. Since a single complex molecule may not obey exact C₂-symmetry, appearance of the two-fold axis in the crystal is a result of statistical disorder. Some atoms in two positions coincide within resolution of the data. High values of the atomic displacement parameters indicate also motility (for non-disordered atoms 0.05 < *U*_{eq} < 0.15). Three short contacts demonstrate possible steric fit between the CH₃ group of toluene and the benzene portion of a benzimidazole moiety [C(14)···CH₃ = 3.26(2) Å, C(19)···CH₃ = 3.40(2) Å and C(15)···CH₃ = 3.46(5) Å]. A water molecule in the crystal structure of the solvent inclusion of **5b** resides on a two-fold crystallographic axis and probably binds the neighbouring complexes by H bonds to the O atoms of disordered benzimidazol-2-one moiety [O(1W)···O(21) = 2.58(1) Å, O(1W)···O(22) = 2.94(1) Å] in infinite helical chains around the four-fold screw axis resulting in channel formation along the *c* axis of the crystal (Fig. 3). In the solvent inclusion crystal of **5b** some toluene was found to exist as a solvent located in the channels between molecules (Fig. 3). All intermolecular contacts of this second toluene molecule exceed 3.7 Å. The 14 largest difference map peaks (from 0.4 to 0.26 e Å⁻³) are situated near this toluene entity. This residual electron density is disposed above the cavity

Table 3 Characteristic dihedral angles between the belt atoms mean plane and the main planes (δ) of the constituent rings A, B, C and D and between consecutive rings as well, and their esd values of planes in **5a**, **5b** and **5c**. Ring A,C = methoxyphenyl; ring B,D = benzimidazolone, *p*-tert-butylmethoxyphenylene

Comp.	Ring	Guest(s)	Dihedral angles/degrees (δ)			
			A	B (B1/B2 ^a)	C	D
5a	M (δ)	<i>b</i>	127.8(1)	122.7(1)	107.1(1)	139.2(1)
5b		8.0(1)	113.7(2)	123.2(2)/137.4(1)	115.4(1)	123.3(1)
5c		0.0(1)/28.3(2)	112.2(1)	115.7(1)	120.3(1)	146.4(1)
5a	A	—	—	80.4(1)	—	—
5b				78.1(3)/84.1(3)		
5c				86.1(1)		
5a	B	—	—	—	73.1(1)	—
5b	B1/B2 ^a				67.5(3)/82.8(2)	
5c					89.6(1)	
5a	C	—	—	—	—	84.8(1)
5b						73.1(2)
5c						84.1(1)
5a	A' ^c	—	—	—	—	89.3(1)
5b						68.8(2)
5c						38.891

^a OD Benzimidazolone groups. ^b OD guests in **5a**. ^c Symmetry equivalent residue of A.

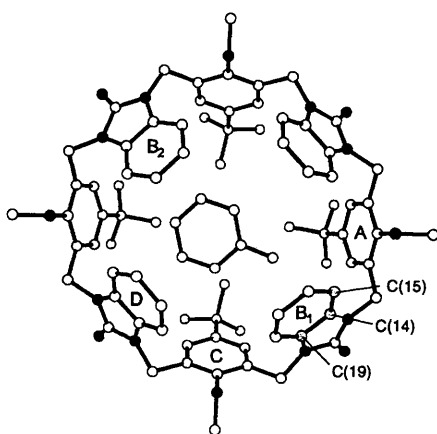


Fig. 2 Top-view of the molecular structure of the **5b**-toluene-water 1:2:1 molecular associate. Only guest site and one benzimidazolone ring location are shown, water molecule is also omitted for the sake of clarity and atom names are shown indicating host-guest interactions.

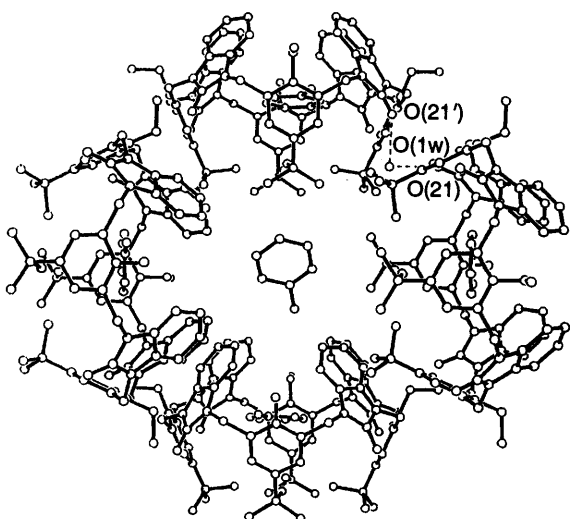


Fig. 3 Top-view of a packing excerpt of the **5b**-toluene-water 1:2:1 associate. Only the second guest site, water interactions (dotted lines) and one benzimidazolone ring location are shown to illustrate channel formation and surroundings.

approximately perpendicular to the main calix plane. About half the toluene molecule occupancy in the channel supposedly stems from statistic disorder of toluene molecules along the

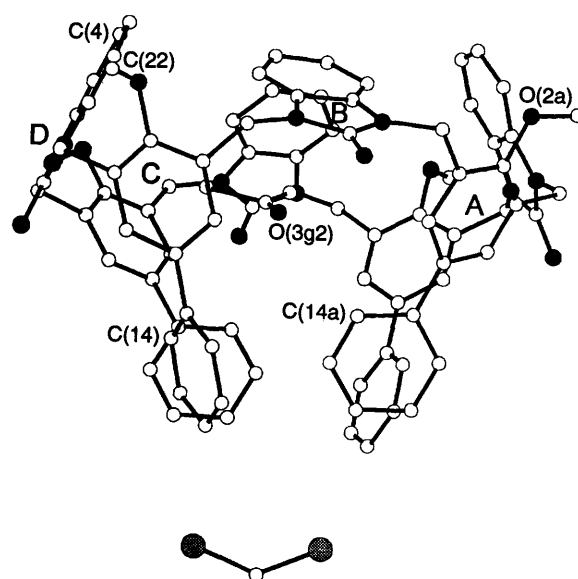


Fig. 4 Side-view of the **5c**-acetone-CH₂Cl₂ 1:1:1 molecular associate. Disordered guest sites of the asymmetric unit are separated into one possible ordered structure model in order to show a plausible location of guest molecules interacting with the host matrix. Atom names shown are indications for the locations of host-guest interactions.

longitudinal channel axis smeared through the macroscopic crystal and might indicate that a 1:2:1 stoichiometry may exist in some more ideal crystals. Nevertheless one concludes that the **5b**-toluene-water crystalline inclusion is both an *endo*-calix and an *exo*-calix complex, *i.e.* a cavitate and a clathrate¹⁴ with a conceived 1:2:1 host-toluene-H₂O stoichiometry. Host molecules in this structure also pack such that one of the benzimidazolone units faces another symmetry centre related mate, though somewhat rotated such that the five-membered rings overlap. Atoms of the concerned moieties are again at about base stacking distances of 3.4–3.6 Å apart from the least-squares planes of counterfacing benzimidazolones.

5c-Acetone-CH₂Cl₂ (1:1:1). Crystal structure model of this solvent inclusion reveals the most elliptical molecular shape for the host (Fig. 4). The puckering of the belt forming atoms also has a maximum value as indicated by the respective least-squares plane (Table 2). The host molecule resides around a two-fold crystallographic axis again, thus having an ideal C₂ symmetry. The arrangement of the molecular planes forming a closed cage is such that they are close to right angles except the last residue (D) which presumably due to the deformations and

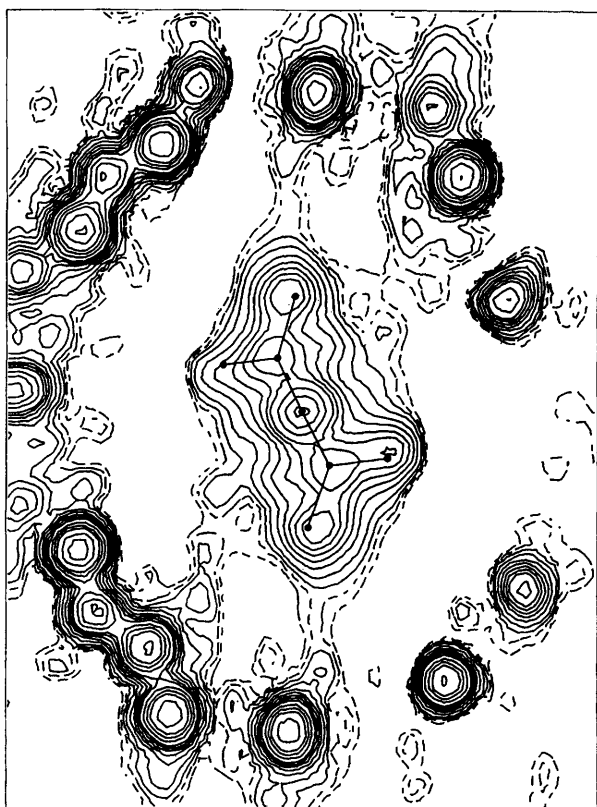


Fig. 5 Electron density cross section in the 'belt plane' height in the **5c**:acetone·CH₂Cl₂ 1:1:1 complex showing complementary fit between host and guest molecules

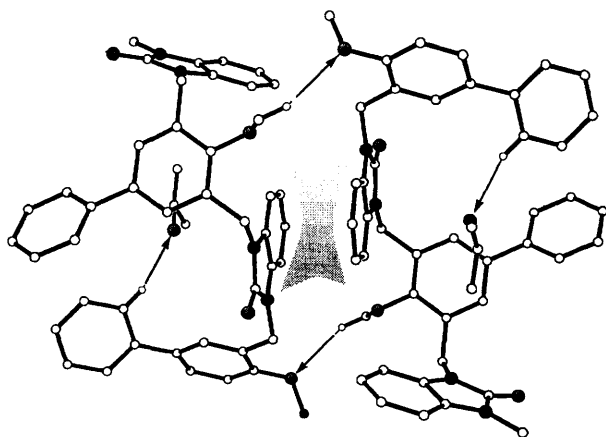


Fig. 6 Displacement of symmetry centre-related benzimidazolone moieties as cut from crystal packing of **5c**:acetone·CH₂Cl₂ 1:1:1 illustrating eventually favourable positions for base stacking

ring closure constraints has the lowest dihedral angle (38.8°, cf. Table 3). Disposition of rings A–D vs. the belt plane is peculiar with the highest dihedral angle among calix[4]- and calix[8]-arenes, especially if one considers that molecule **5c** does form a cage, not a pleated loop or chair.^{15,16} All these findings indicate considerable strain in the host molecule, also indicated by the significant deviations from planarity of the aromatic rings A–D. However, this strain is not manifested in disordering of planar constituents of the macro ring in contrast to **5b**. The inclusion compound of **5c** is again an *endolexo*-calix species.

Both acetone and dichloromethane guest molecules lie on, or very close to, the C₂ symmetry element thus yielding a static disordered crystal structure model for the guests. The shape of the cavity in the belt cross section and interatomic distances indicate complementary steric (C–H···C) and electrostatic fit (via weak C–H···O interactions to the outer phenyl moiety of

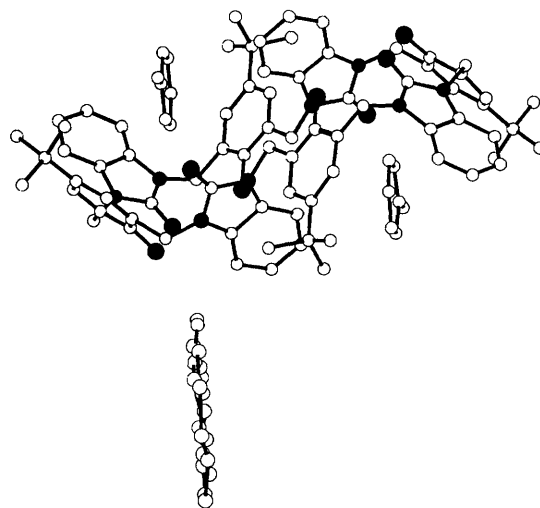


Fig. 7 Side-view of the **5f**-toluene 1:3 molecular associate indicating like a huge chair conformation of the host, with guest molecule locations and atom names of those involved in H-bonding interactions

the methoxybiphenylene group) of the acetone molecule to the host that completely encloses this guest entity [Fig. 5, O(3g2)···H(14a)–C(14a) = 160(1)°, H(14)···O(3g2) = 2.35(1) Å]. This H atom also binds to the dichloromethane guest molecule, which is placed outside of the cavity near to the rim of the molecule [bifurcated H-bonds; Cl(1)···H(14a) = 2.91(1) Å, Cl(1)···H(14a)–C(14) = 129(1)°]. The Cl(2) atoms also alternate, as dictated by the two-fold symmetry, in weak interaction with the other phenyl H(4) atom [Cl(2)···H(4) = 3.18(1) Å, Cl(2)···H(4)–C(4) = 138(1)°]. There is a further weak presumed C–H···O interaction between symmetry related methoxy groups [O(2A)···H(22A) = 2.58(1) Å, O(2A)···H(22A)–C(22) = 158(1)°]. A further interesting fit develops between the benzimidazolone moieties of molecules related by a centre of symmetry (Fig. 6) as in the cases of hosts **5a** and **5b**. Characteristic distances resembling base stacking are around 3.49 Å (mean value of the distances of the benzimidazolone atoms from the symmetry related plane) for this probable interaction.

5f·Toluene (1:3). Here the calixarene molecule sits on a crystallographic centre of symmetry (Fig. 7). The host molecule creates two antiparallel partial cone-like cavities thus adopting a huge chair-like conformation.¹⁶ This conformation is supported by intramolecular O···O type H-bonds between the carbonyl O atom of benzimidazol-2-one (B) and the hydroxy groups of two neighbouring *tert*-butylphenol entities [residues A and C, O(7)···O(1) = 2.840(4) Å, H(1)–O(2) = 2.04(1) Å, O(1)–H(1)···O(2) = 166(5)° and O(2)···O(3) = 2.669(4) Å, H(3)–O(2) = 1.85(1) Å, O(3)–H(3)···O(2) = 173(5)°]. Fig. 7 shows two toluene molecules held in a quasi *endo*-calix position. All distances between host and guests are more than 3.64(1) Å. In the crystal structure of **5f**·toluene 1:3 the solvent molecules occupy not only intramolecular cavities, but also intermolecular voids of the crystal lattice. These latter toluene molecules are statistically disordered and lie around another independent centre of symmetry. It is apparent from the packing that this type of solvent molecule can be understood to play a role inhibiting the development of the stacking-like fit of benzimidazolone rings related in the crystal packing of **5a**–**c** by the centres of symmetry. However, instead of benzimidazolones two of the symmetry related phenol moieties stack with interplanar distances of again 3.4–3.6 Å. One may speculate that the appearance of this chair-like conformation here, the shape that is found for the classic calix[8]arenes, is caused in the case of **5f** just by the stacking of the conserved phenol moiety and by the third solvent molecule in a concerted manner. The solvent inclusion of **5f** is again both an *endo*- and *exo*-calix complex with 1:3 host–guest stoichiometry.

Conclusions

The present results show that calixarene architecture consisting of unconventional building blocks, instead of the different *para*-substituted phenolic subunits, provide new examples of the potential of the basic calixarene framework. Thus, the incorporation of benzimidazol-2-one unit yields a new type of calix container. The X-ray structure analyses of the crystalline inclusion compounds of the respective heterocalix[8]arenes illustrate the possibility of transferring the structural behaviour of calix[4]arenes (cage forming ability) to calix[8]arene systems using this type of construction.

All host molecules in this study, except **5f**, obey C_2 molecular symmetry and form almost perfectly closed cages. In comparison with the shape of [4]-calixes which also form cage structures sometimes with C_2 molecular symmetry but in general using more diverse molecular symmetries (from C_s to C_4) to form their host shapes, one may conclude that hetero-calixes are more robust than the similar eight-membered calixarenes^{13,15,16} in spite of the presence of the obvious, somewhat guest depending molecular strain. The values of the dihedral angles of the A–D plane components towards the belt region (Table 1, row 1), as compared with the mean value for calix[4]arenes [$\delta = 124(2)^\circ$] indicates that these molecules are inherently mobile enough to adopt the structures demanded by different guests as demonstrated here. Still, they are obviously better suited for molecular encapsulation than traditional calix[8]arenes having their cage forming ability sustained. One may also speculate, that this behaviour is driven by the polarity of the applied solvents and co-solvents, as illustrated by the X-ray structures. Development of closed basket-like host shapes seems also to be a concerted effect with the involvement of base-stacking-like interactions between aromatic residues and guest solvents. In the cases of **5a–c** stacking is realized through symmetry centres related benzimidazolone units providing the basket-shape, while in **5f** it is affected by phenol moieties and yields a more open chair-type conformation.

Experimental

Synthesis

Melting points were taken on a Kofler apparatus (Reichert, Wien). The ¹H NMR spectra were recorded on a Bruker AC-200 (200 MHz), WM-250 (250 MHz) and WM-300 (300 MHz) with Me₄Si as internal reference. δ values in ppm; J values in Hz. Mass spectra were obtained with AEI MS-30, MS-50 and Kratos Concept 1H spectrometers. Al₂O₃ (60 G neutral, Merck) and SiO₂ (63–100 μ m, Merck) were used for column chromatography and sephadex (LH-120, Fluka) for gel-filtration.

Compounds **1** and **2a–d**^{8–10} were prepared according to literature procedures.

2,6-Bis[(2-oxobenzimidazol-1-yl)methyl]anisole **3a–d**; general procedure

N-Propen-2-ylbenzimidazol-2-one (**1**) (13.7 g, 30 mmol) was added to a stirred suspension of sodium hydride (1.4 g suspension 60%, 35 mmol) in anhydrous DMF (100 ml). After 30 min of stirring the respective bis(bromomethyl) compound (**2a–d**, 15 mmol) was added. The mixture was heated at 80 °C for 4 h, then cooled to room temperature and stirred overnight. A solution of sulfuric acid (40 ml) in water (20 ml) was added dropwise and stirring of the mixture was continued (overnight). Water (300 ml) was poured into the reaction mixture. The crude product was filtered off, washed with water and recrystallized. Specific details are given for each compound.

2,6-Bis[(2-oxobenzimidazol-1-yl)methyl]anisole (3a). From **1** and **2a**: 87% colourless powder, mp >300 °C [from MeOH–acetone (1:1)] (Found: C, 68.81; H, 5.06; N, 13.62. Calc. for C₂₃H₂₀N₄O₃: C, 68.99; H, 5.03; N, 13.99%) δ_{H} (200 MHz; [²H₆]DMSO) 3.95 (3 H, s, OMe), 5.05 (4 H, s, CH₂), 6.75–7.0 (11

H, m, Ph) and 11.0 (2 H, s, NH); m/z (EI, 70 eV) 400.1529 (M⁺).

4-tert-Butyl-2,6-bis[(2-oxobenzimidazol-1-yl)methyl]anisole (3b). From **1** and **2b**: 80% colourless crystals, mp 295–296 °C [from MeOH–acetone (1:2)] (Found: C, 70.90; H, 6.59; N, 11.91. Calc. for C₂₇H₂₈N₄O₃: C, 71.03; H, 6.18; N, 12.2%) δ_{H} (300 MHz; [²H₆]DMSO) 1.0 (9 H, s, Bu^t), 3.9 (3 H, s, OMe), 5.05 (4 H, s, CH₂), 6.9–7.05 (10 H, m, Ph) and 11.0 (2 H, s, NH); m/z (EI, 70 eV) 456.2170 (M⁺).

2,6-Bis[(2-oxobenzimidazol-1-yl)methyl]-4-phenylanisole (3c). From **1** and **2c**: 70% colourless needles, mp 254 °C (from MeOH) (Found: C, 72.68; H, 5.22; N, 11.43. Calc. for C₂₉H₂₄O₃N₄: C, 73.09; H, 5.08; N, 11.76%) δ_{H} (300 MHz; [²H₆]DMSO) 3.95 (3 H, s, OMe), 5.2 (4 H, s, CH₂), 6.8–7.3 (15 H, m, Ph) and 11.0 (2 H, s, NH); m/z (DCI pos., methane) 477 [(M + H)⁺].

4-Methoxy-2,6-bis[(2-oxobenzimidazol-1-yl)methyl]anisole (3d). From **1** and **2d**: 80% colourless crystals, mp 281 °C (from MeOH) (Found: C, 66.66; H, 5.18; N, 13.03. Calc. for C₂₄H₂₂O₄N₄: C, 66.97; H, 5.15; N, 13.02%) δ_{H} (300 MHz; [²H₆]DMSO) 3.47 (3 H, s, OMe), 3.86 (3 H, s, OMe), 5.02 (4 H, s, CH₂), 6.9–7.1 (8 H, m, Ph) and 10.95 (2 H, s, NH); m/z (DCI pos., methane) 431 [(M + H)⁺].

Heterocalixarenes **4a–c** and **5a–d**; general procedure

The respective benzimidazolone (**3a–d**, 15 mmol) was added to a stirred suspension of sodium hydride (30 mmol) in anhydrous DMF (200 ml). The mixture was stirred at room temperature for 2 h and filtered through a sintered glass funnel. The filtrate was made up to 250 ml with additional anhydrous DMF. This solution and a solution of the corresponding dibromide (**2a–d**, 15 mmol) in DMF (250 ml) were simultaneously added to a stirred suspension of caesium carbonate (6 g, 18 mmol) in DMF (500 ml) at 80 °C during 8 h. Stirring was continued for an additional 24 h. This mixture was worked up by evaporation, treatment with MeOH–CH₂Cl₂ (1:1), filtering off and concentration of the filtrate. Purification was carried out by column chromatography on SiO₂ followed by column chromatography on Al₂O₃ or gel-filtration with sephadex. Specific details are given for each compound.

1²,5²-Dimethyl-3²,7²-dioxo-1(1,3),5(1,3)-dibenzena-3(1,3),7(1,3)-dibenzimidazolacyclooctaphane (4a) and **1²,5²,9²,13²-tetramethoxy-3²,7²,11²,15²-tetraoxo-1(1,3),5(1,3),9(1,3),13(1,3)-tetrabenzena-3(1,3),7(1,3),11(1,3),15(1,3)-tetrabenzimidazolacyclohexadecaphane (5a)**. From **2a** and **3a**: SiO₂ [eluent CH₂Cl₂–acetone–MeOH (6:1:0.2)]; Al₂O₃ [eluent CH₂Cl₂–ethyl acetate–PrⁱOH (10:1:1)]. **4a**: 3.4% colourless crystals, mp >300 °C (Found: C, 71.81; H, 4.77; N, 11.19. Calc. for C₃₂H₂₈N₄O₄: C, 72.17; H, 5.30; N, 10.52%) δ_{H} (200 MHz; CDCl₃) 4.05 (6 H, s, OMe), 4.2, 5.75 (8 H, dd, J 2, CH₂), 7.1–7.4, 5.9–6.3 (14 H, m, Ph); m/z (EI, 70 eV) 532.2107 (M⁺). **5a**: 7.2% colourless crystals, mp >300 °C (Found: C, 70.38; H, 5.28; N, 10.13. Calc. for C₆₄H₅₆N₈O₈·H₂O: C, 70.97; H, 5.40; N, 10.34%) δ_{H} (200 MHz; CDCl₃) 4.01 (12 H, s, OMe), 5.15 (16 H, s, CH₂), 6.5–7.35 (28 H, m, Ph); m/z (FAB) 1065.5 [(M + H)⁺].

1⁵,5⁵-Di-tert-butyl-1²,5²-dimethoxy-3²,7²-dioxo-1(1,3),5(1,3)-dibenzena-3(1,3),7(1,3)-dibenzimidazolacyclooctaphane (4b) and **1⁵,5⁵,9⁵,13⁵-tetra-tert-butyl-1²,5²,9²,13²-tetramethoxy-3²,7²,11²,15²-tetraoxo-1(1,3),5(1,3),9(1,3),13(1,3)-tetrabenzena-3(1,3),7(1,3),11(1,3),15(1,3)-tetrabenzimidazolacyclohexadecaphane (5b)**. From **2b** and **3b**: SiO₂ [eluent CH₂Cl₂–MeOH–acetone (5:1:1)]; sephadex (eluent CHCl₃). **4b**: 5% colourless crystals, mp 241 °C (Found: C, 74.35; H, 6.82; N, 8.50. Calc. for C₄₀H₄₄N₄O₄: C, 74.51; H, 6.88; N, 8.69%) δ_{H} (300 MHz; CDCl₃) 1.0 (18 H, s, Bu^t), 4.0 (6 H, s, OMe), 5.75, 4.15 (8 H, dd, J 2, CH₂) and 7.1–7.4, 5.9–6.2 (12 H, m, Ph); m/z (EI, 70 eV) 644.3369 (M⁺). **5b**: 15% colourless crystals; mp 202 °C (Found: C, 73.24; H, 6.71; N, 8.38. Calc. for C₈₀H₈₈N₈O₈·H₂O: C, 73.48; H, 6.94; N, 8.57%) δ_{H} (300 MHz; CDCl₃) 1.0 (36 H, s, Bu^t), 3.95 (12 H, s, OMe), 5.05 (16 H, s, CH₂), 6.25–7.2 (24 H, m, Ph); m/z (FAB) 1289.7 [(M + H)⁺].

1^{2,5},9²,13²-Tetramethoxy-1⁵,5⁵,9⁵,13⁵-tetraphenyl-3²,7²,11²,15²-tetraoxo-1(1,3),5(1,3),9(1,3),13(1,3)-benzena-3(1,3),7(1,3),11(1,3),15(1,3)-tetrabenzimidazolacyclohexadecaphane (5c). From **2c** and **3c**; SiO₂ [eluent CH₂Cl₂-acetone (5:1)]; 17% colourless crystals, mp 232 °C (Found: C, 75.19; H, 6.11; N, 7.53. Calc. for C₈₈H₇₂O₈N₈·3Me₂CO: C, 75.47; H, 5.88; N, 7.26%) δ_H(300 MHz; CDCl₃) 3.95 (12 H, s, OMe), 5.0 (16 H, s, CH₂) and 6.45–7.3 (44 H, m, Ph); *m/z* (DCI pos., methane) 1369.7 [(M + H)⁺].

1^{2,5},5^{2,5},9^{2,5},13^{2,5}-Octamethoxy-3²,7²,11²,15²-tetraoxo-1(1,3),5(1,3),9(1,3),13(1,3)-tetrabenzena-3(1,3),7(1,3),11(1,3),15(1,3)-tetrabenzimidazolacyclohexadecaphane (5d). From **2d** and **3d**; SiO₂ [eluent CHCl₃-acetone (10:1)]; 35% colourless crystals, mp 281 °C (Found: C, 63.98; H, 5.36; N, 8.65. Calc. for C₆₈H₆₄O₁₂N₈·CHCl₃: C, 63.52; H, 5.02; N, 8.59%) δ_H(300 MHz; [²H₆]DMSO) 3.45 (12 H, s, OMe), 3.9 (12 H, s, OMe), 5.2 (16 H, s, CH₂), 6.4–7.3 (24 H, m, Ph); *m/z* (DCI pos., methane) 1185 [(M + H)⁺].

Heterocalixarenes **5e** and **5f**, general procedure

A solution of **5a** or **5b** (0.075 mmol) in dry dichloromethane (10 ml) was added dropwise over 2 h to a solution of BBr₃ in dry dichloromethane (1 M, 2.5 ml) at room temperature. The mixture was stirred overnight; then water (10 ml) was added. The organic layer was separated, evaporated and recrystallized from MeOH. Specific details are given for each compound.

1^{2,5},9²,13²-Tetrahydroxy-3²,7²,11²,15²-tetraoxo-1(1,3),5(1,3),9(1,3),13(1,3)-tetrabenzena-3(1,3),7(1,3),11(1,3),15(1,3)-tetrabenzimidazolacyclohexadecaphane (5e). From **5a**; 92% of colourless powder, mp >300 °C (from MeOH) (Found: C, 68.54; H, 4.91; N, 11.18. Calc. for C₆₀H₄₈O₈N₈·2 H₂O: C, 68.96; H, 5.01; N, 10.72%) δ_H(250 MHz; [²H₆]DMSO) 5.1 (16 H, s, CH₂), 6.4–7.2 (24 H, m, Ph) and 9.65 (4 H, s, OH); *m/z* (FAB) 1009.2 [(M + H)⁺].

1⁵,5⁵,9⁵,13⁵-Tetra-*tert*-butyl-1^{2,5},5^{2,5},9^{2,5},13^{2,5}-tetrahydroxy-3²,7²,11²,15²-tetraoxo-1(1,3),5(1,3),9(1,3),13(1,3)-tetrabenzena-3(1,3),7(1,3),11(1,3),15(1,3)-tetrabenzimidazolacyclohexadecaphane (5f). From **5b**; 60% of colourless powder, mp 240–241 °C (from MeOH) (Found: C, 73.25; H, 6.46; N, 8.93. Calc. for C₇₆H₈₀O₈N₈·MeOH: C, 73.08; H, 6.69; N, 8.85%) δ_H(300 MHz; [²H₆]DMSO) 1.0 (36 H, s, Bu^t), 5.05 (16 H, s, CH₂), 6.5–7.0 (24 H, m, Ph) and 9.5 (4 H, s, OH); *m/z* (FAB) 1224.9 [(M + H)⁺].

Crystallography

Crystals of the inclusion compounds suitable for X-ray diffraction studies were invariably obtained through dissolution of the respective hosts and on slow solvent evaporation. Since inclusion compounds of **5c** and **5f** proved unstable in open air, they were sealed in glass capillaries and mounted for measurement.

Crystal and molecular structures were determined from data collected on CAD-4 diffractometers with graphite monochromatized Cu-Kα radiation (λ = 1.54178 Å), at reduced temperatures (200 K) for **5a**·CH₂Cl₂ (1:2), **5b**·toluene·H₂O (1:2:1) and **5f**·toluene (1:3) and at 298 K for **5c**·acetone·CH₂Cl₂ (1:1:1). Lattice constants and orientation matrices were refined by least-squares fits of 25 reflections in θ ranges 14.2–18.61° for the solvent inclusion of **5a**, 14.3–17.6° for **5b**, 26.93 and 43.30° for **5c**, and 13.7–17.4° for **5f**. Intensities were obtained by profile analysis¹⁷ for the inclusion compounds of **5a**, **5b** and **5f** and by HELENA¹⁸ for **5c**. Three standard reflections were measured after every 100 reflections for the inclusions of **5a**, **5b** and **5f**, and every 300 for the **5c** inclusion, showing no decay of the crystals during the data collection in all cases. Initial structure models were obtained by direct methods (SHELXS-86¹⁹). All independent reflections with non-zero intensities were used to refine the final models to convergence by full matrix least-squares (SHELXL-93²⁰). Isotropic thermal parameters were applied to the ordered non-hydrogen atoms in all structures. Positions of carbon-bonded hydrogen atoms were calculated

from geometrical considerations and were refined as constrained to bonding carbon atoms. H atoms of the water molecule in the inclusion compound of **5b** and phenol hydrogen atoms in the solvent inclusion of **5f** were located on difference electron density maps and were refined constrained to the parent oxygen atoms. Neutral atom scattering factors were taken from *International Tables for X-ray Crystallography*.²¹ Unit cell parameters and other crystal data are given in Table 1.

Compound **5a**·CH₂Cl₂ (1:2) crystallizes in the orthorhombic *Pbcn* space group. The CH₂Cl₂ guest molecule is disordered and occupies at least three neighbouring positions. Their site occupation factors (SOF) of 0.50(1), 0.25(1) and 0.25(1) resulted from refinement. Parameters of guest molecules in these positions were refined isotropically using geometrical restraints for covalent distances of an ideal molecule²² as a target.

Compound **5b**·toluene·H₂O (1:2:1) crystallizes in the tetragonal *I4₁/acd*. Positions of disordered guest atoms were found in difference Fourier maps. Regular hexagons with C–C = 1.39 Å were fitted to these atoms. On successive difference syntheses the positions of terminal CH₃ groups were localized and geometrical constraints C–CH₃ = 1.50 Å were also applied to idealize flat toluene molecules which were then refined as rigid groups with common temperature factors. The disordered atoms in the calix were refined using individual isotropic parameters. SOF of guest molecules were refined and values of 0.50(1) and 0.22(1) were obtained for toluene guest molecules within the calix and external to it, respectively.

The *C2/c* space group of the compound **5c**·acetone·CH₂Cl₂ (1:1:1) was ascertained from the refinement such that the alternative *accentric Cc* space group model was also refined. However, it was deemed less probable, since no improvement in the *R* values and in the model were obtained. Populations for the disorder guest sites were not refined, but adjusted continuously throughout the refinement such that physically reasonable atomic displacement values resulted. Only two possible sites were considered for either guests, although from residual electron density it became obvious that there may be more than two sites. However, the physical reality of a further complicated room-temperature model may well be questioned, and for this reason no further attempts were made to introduce populations that would conceivably lead to further minor occupations. All hydrogen atoms, less the two missing for the dichloromethane guest and the six for the acetone guest, were generated from geometric evidences and kept riding on their mother carbon atoms. The physical reality of the omitted guest hydrogen atoms might also be questioned, therefore we did not include them in the scattering model.

The crystal of **5f**·toluene (1:3) is triclinic *P* $\bar{1}$ (No. 2). The pair of guest toluene sites outside host **5f** are disordered and reside near two independent centres of symmetry. Two positions with SOF 0.31(1) and 0.19(2) were found for these partially occupied toluene molecule sites. Consequently this guest molecule is disordered in its intermolecular void in the crystal lattice in four orientations. The other guest toluene, closer to the calix molecule, also occupies two positions related by another centre of symmetry with an SOF of 0.45(1).

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