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# Cyclodextrin stationary phases for the gas–solid chromatographic separation of inorganic gases

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## ABSTRACT

Cyclodextrins linked to silica gel are used as gas–solid chromatographic stationary phases. They provide an effective means for separating a wide variety of gases. Evaluation of different cyclodextrin columns and the analogous silica gel support column with inorganic gas standards is reported. Separation selectivities and efficiencies differ between silica gel and the cyclodextrin phases. Capacity factors and chromatograms are presented for these gas–solid chromatographic stationary phases. The native cyclodextrin stationary phases appear to retain gases via at least two different retention mechanisms.

## INTRODUCTION

Gas-solid chromatography (GSC) is a technique used for the separation of gases and compounds with low boiling points. Packed columns, and more recently, porous-layer open-tubular (PLOT) or support-coated open-tubular (SCOT) [1–3] columns are preferred for the separation of these highly volatile materials. Many GSC stationary phases, including molecular sieves [4–6], alumina [7], silica gel [8,9], porous polymers [10] and charcoal [11,12] have been cited as separating inorganic gases. For the separation of argon, oxygen and nitrogen, molecular sieves [13–15] and porous polymers [16,17] are widely used. Several review articles have summarized the separation of inorganic gases on many different stationary phases [18–21]. Generally, gas–liquid chromatographic (GLC) stationary phases have limited applicability in the analysis of compounds such as $H_2$, $O_2$, $N_2$, CO and Ar due to the low solubility of these gases in liquid phases [19].

One of the problems associated with the analysis of a wide range of gases is the non-universality of columns. A column that is ideal for one separation may be completely useless for another (*e.g.* molecular sieves easily separate oxygen, nitrogen and argon, but irreversibly retain carbon diodixe and water [21]). The usual solution to this problem is to use several different types of columns.

The cyclodextrin molecule has been reported to be able to form stable complexes with gases. Inclusion complexes of α-cyclodextrin with oxygen and carbon dioxide are formed when the gases are held at high pressure for several days over an aqueous solution of cyclodextrin. The cyclodextrin-guest crystalline complexes are stable for long periods of time. α-Cyclodextrin complexes 0.3 mol of oxygen and 1.4 mol of carbon dioxide per mole of cyclodextrin [22]. Carbon monoxide, unlike carbon dioxide, does not form an inclusion complex with α-cyclodextrin. Similarly, lower noble gases (helium, neon and argon) do not form inclusion complexes with α-cyclodextrin, whereas the larger members of the group (krypton and xenon) do when under high pressure [23]. GSC separation of a wide range of low-molecular-mass ($C_1$–$C_7$) hydrocarbons using cyclodextrin-bonded phases recently has been reported [24].

Cyclodextrins previously have been used as coat-

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ings for chromatographic stationary phases [25]. Presently, many researchers are reporting the use of amorphous derivatized cyclodextrins as GLC chiral stationary phases [26–30].

Cyclodextrins are cyclic oligosaccharides composed of D(+)-glucopyranose units which are linked by $\alpha$-(1,4) bonds. The cyclized glucopyranose units form conical structures, with secondary hydroxyls (12 for $\alpha$-CD) surrounding the wider end and the primary hydroxyls (6 for $\alpha$-CD) on the opposite end. The top and bottom of the structure are polar, due to the hydroxyl groups, while the interior of the cavity is non-polar. $\alpha$-, $\beta$- and $\gamma$-cyclodextrins are differentiated by the number of glucopyranose subunits (6, 7 and 8, respectively) in the structure. The internal diameter of $\alpha$ and $\beta$-cyclodextrin's cavity are 4.5 and 7 Å, respectively, and molecules of suitable size can form inclusion complexes. Many recent mechanistic studies involving chromatographic separations on cyclodextrin and derivatized cyclodextrin stationary phases have cited multiple retention mechanisms [24,31–33]. Depending on the chromatographic conditions and the nature of the analyte, either inclusion complexation or external adsorption with the cyclodextrin moiety can contribute to retention and separation.

## EXPERIMENTAL

### Instrumentation

A Hewlett-Packard (Avondale, PA, USA) 5890 Series II gas chromatograph equipped with a packed column injection port, thermal conductivity detector, and a liquid nitrogen cryogenic coolant system was utilized in this study. The injector and detector were set at 200°C. The oven temperature program, unless otherwise noted, was 30°C for 1 min, then increasing at 10°C/min to 180°C. The temperature was held at 180°C until the last component eluted (which was determined from prior experiments). Data collection was accomplished with a Hewlett-Packard 3396B Series II integrator. Helium was used as the carrier gas for all separations, with a flow-rate of approximately 20 ml/min. The void time for all columns was measured with repetitive injections of (150 $\mu$l) hydrogen. The void time is the time required for an unretained component to elute. Hamilton gas-tight syringes were used for all injections.

### Stationary phases

Stationary phases were obtained from Advanced Separation Technologies (Whippany, NJ, USA). All separations were accomplished on 40-$\mu$m silica supports (preparative HPLC supports). The stationary phases were: Cyclobond II (CBI), Cyclobond I Acetylated (CBI AC), Cyclobond III (CBI-II), Cyclobond III Acetylated (CBIII AC), silica gel, silica gel containing the 6–10 atom epoxy-terminated linkage [34,35] used to bond cyclodextrin to silica gel (Epoxy) and $\beta$-cyclodextrin directly bonded to silica gel (HIGH) which contains a higher stationary phase loading than CBI. Cyclobond I (CBI) is the $\beta$-cyclodextrin-bonded phase and Cyclobond III (CBIII) is the $\alpha$-cyclodextrin-bonded phase. Stationary phases were packed into 91 cm × 2.1 mm I.D. stainless-steel tubing (Supelco, Bellefonte, PA, USA). All columns were prepared by dry packing, using tapping or vibrating to ensure a compact bed. Approximately 1.5 g of stationary phase were loaded into each 3-ft. column. The columns were activated at 280–300°C for several hours before use commenced. Conditioning removes water and any residual solvent remaining from the cyclodextrin/ epoxy bonding procedure. As long as there is no oxygen in the flow stream the cyclodextrin stationary phases appear to be stable at high temperatures.

### Chemicals

Gases were obtained from LIF-O-GEN (Cambridge, MD, USA): oxygen; MG Industries (Valley Forge, PA, USA): ethylene oxide and nitrogen dioxide; Scott Specialty Gases (Plumsteadville, PA, USA): carbon dioxide, carbon monoxide, carbonyl sulfide, hydrogen, hydrogen sulfide, nitrous oxide, sulfur dioxide and sulfur hexafluoride; Spectra Gases (Newark, NJ, USA): krypton and neon. Gases were sampled directly from cylinders or from gas sampling bulbs. Approximately 2–5 $\mu$l of gas were injected into the gas chromatograph.

### RESULTS AND DISCUSSION

Six cyclodextrin GSC stationary phases, along with the silica gel support for comparison, were evaluated in terms of retention and separation characteristics of selected inorganic gases. Several "families" (i.e., noble, nitrogen containing, sulfur based, etc.) of gases were chosen in order to evaluate the

TABLE I

COMPARISON OF INORGANIC GAS CAPACITY FACTORS ($k'$) BY STATIONARY PHASE AND ELUTION ORDER ON SILICA GEL

| Gases | $k'$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | Silica | Epoxy[a] | CBIII[b] | CBIIIAC[c] | CBI[d] | HIGH[e] | CBIAC[f] |
| Hydrogen | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Nitrogen | 0.32 | 0.27 | 0.30 | 0.27 | 0.38 | 0.43 | 0.27 |
| Carbon monoxide | 0.49 | 0.36 | 0.39 | 0.38 | 0.48 | 0.64 | 0.39 |
| Krypton | 0.69 | 0.76 | 0.94 | 0.94 | 1.13 | 1.42 | 0.82 |
| Nitrogen dioxide[g] | 1.12 | 0.95 | 0.89 | 0.98 | 1.01 | 1.00[i] | 0.82 |
| Sulfur hexafluoride | 3.81 | 3.28 | 4.42 | 4.23 | 5.01 | 7.89 | 3.80 |
| Nitrous oxide | 5.70 | 4.77 | 5.07 | 4.75 | 5.58 | 6.95 | 4.41 |
| Carbon dioxide | 6.32 | 4.94 | 5.01 | 4.69 | 5.47 | 7.03 | 4.40 |
| Carbonyl sulfide | 8.67 | 7.66 | 9.20 | 8.74 | 10.04 | 12.28 | 8.25 |
| Ethylene oxide | 9.86 | 9.55 | 11.58 | 11.19 | 12.71 | 16.46 | 10.95 |
| Hydrogen sulfide | 10.44 | 8.23 | 8.97 | 8.44 | 9.64 | 12.17 | 8.19 |
| Sulfur dioxide | 21.55[h] | 16.87 | 16.21 | 15.84 | 16.79 | 19.29 | 15.92 |

[a] Epoxy-terminated 6–10 atom linkage connecting cyclodextrin (CD) to silica gel.
[b] CBIII is native $\alpha$-CD bonded to silica gel.
[c] CBIIIAC is acetylated $\alpha$-CD bonded to silica gel.
[d] CBI is native $\beta$-CD bonded to silica gel.
[e] HIGH is a high-density surface coverage $\beta$-CD on silica gel (2–3 times more coverage than CBI).
[f] CBIAC is acetylated $\beta$-CD directly bonded to silica gel.
[g] Chromatographed isothermally at 135°C.
[h] Elution occured only when final temperature of temperature program was 200°C.
[i] The first of two peaks past the air peak was used as the $NO_2$ peak.

TABLE II

RATIO OF INORGANIC GAS CAPACITY FACTORS OBTAINED ON CYCLODEXTRIN STATIONARY PHASES *VERSUS* SILICA GEL

See Table I or text for indications of phases.

| Inorganic gases | $\dfrac{k'_{Epoxy}}{k'_{Silica}}$ | $\dfrac{k'_{CBIII}}{k'_{Silica}}$ | $\dfrac{k'_{CBIIIAC}}{k'_{Silica}}$ | $\dfrac{k'_{CBI}}{k'_{Silica}}$ | $\dfrac{k'_{HIGH}}{k'_{Silica}}$ | $\dfrac{k'_{CBIAC}}{k'_{Silica}}$ |
|---|---|---|---|---|---|---|
| Nitrogen | 0.84 | 0.93 | 0.86 | 1.19 | 1.35 | 0.84 |
| Carbon monoxide | 0.74 | 0.79 | 0.77 | 0.99 | 1.31 | 0.79 |
| Krypton | 1.09 | 1.35 | 1.35 | 1.63 | 2.05 | 1.18 |
| Nitrogen dioxide | 0.85 | 0.79 | 0.87 | 0.90 | 0.89 | 0.73 |
| Sulfur hexafluoride | 0.86 | 1.16 | 1.11 | 1.32 | 2.07 | 1.00 |
| Nitrous oxide | 0.84 | 0.89 | 0.83 | 0.98 | 1.22 | 0.77 |
| Carbon dioxide | 0.78 | 0.79 | 0.74 | 0.87 | 1.11 | 0.70 |
| Carbonyl sulfide | 0.88 | 1.06 | 1.01 | 1.16 | 1.42 | 0.95 |
| Ethylene oxide | 0.97 | 1.17 | 1.14 | 1.29 | 1.67 | 1.11 |
| Hydrogen sulfide | 0.79 | 0.86 | 0.81 | 0.92 | 1.17 | 0.78 |
| Sulfur dioxide | 0.78 | 0.75 | 0.74 | 0.78 | 0.90 | 0.74 |

overall applicability of these stationary phases. Table I lists the gases used in this investigation. Capacity factors ($k'$) for the compounds are listed by stationary phase and by the elution order on silica gel. This table shows that the gases chromatographed in this study were all more strongly adsorbed on $\beta$-cyclodextrin (CBI) than $\alpha$-cyclodextrin (CBIII), with the high-surface-density $\beta$-cyclodextrin (HIGH) giving the greatest retention (of the cyclodextrin phases). Native cyclodextrin stationary phases retained the gases more than the corresponding acetylated cyclodextrin stationary phase. The epoxy silanized silica gel generally showed the least retention for the analytes in this study.

Table II lists the capacity factor ratios of the gases analyzed on the epoxy and cyclodextrin column *versus* the silica gel column. Values less than one indicate that the chromatographed compound had a longer retention time on the silica gel column, while values greater than one indicate that the analyte gases were more strongly retained on the cyclodextrin-derivatized silica gel.

In general, the silica gel column showed greater retention for the more polar gases and those with multiple bonds (*e.g.*, inorganic oxides). All cyclodextrin-based columns tended to retain the non-polar, symmetrical gases or those with only single bonds (*e.g.*, sulfur hexafluoride, krypton, ethylene oxide) to a greater extent. Clearly, the native cyclodextrin stationary phases were significantly different from their peracetyl-derivatized analogues. This is particularly evident for the high-coverage, directly bonded stationary phase (*i.e.*, HIGH). These sta-

tionary phases seemed to retain polar gases and with multiple bonds as much (or more in some cases) as silica gel. However, unlike silica gel, cyclodextrins also retained the less polar molecules. Most likely, the explanation for this lies with cyclodextrins' ability to retain molecules via at least two different mechanisms [24]. Analytes such as krypton and ethylene oxide tend to form inclusion complexes with cyclodextrin under these experimental conditions, while the more polar oxides tend to be retained by surface adsorption to the hydroxyl group (as in silica gel).

Often there are selectivity differences between silica gel and cyclodextrin based stationary phases. For example, cyclodextrin phases retain ethylene oxide considerably more than hydrogen sulfide, while the opposite elution order was found for silica gel. Table III shows that the separation factor for ethylene oxide and hydrogen sulfide is 0.94 on silica gel, which increases on the epoxy column to 1.16, and stabilizes between 1.29 (CBI) and 1.35 (directly bonded $\beta$-cyclodextrin, HIGH) on the cyclodextrin columns. To a much smaller extent, nitrous oxide is eluted slightly later than carbon dioxide on cyclodextrin phases, while again, the opposite elution order occurs with silica gel.

Variations in the size of separation factors between classes of columns (silica gel, epoxy and cyclodextrins) also are observed. The separation factor ($\alpha$) for carbonyl sulfide and carbon dioxide on silica gel is 1.37, which increases to 1.55 on the epoxy column and fluctuates between 1.75 on the directly bonded $\beta$-cyclodextrin (HIGH) column

TABLE III

RATIO OF INORGANIC GAS SEPARATION FACTORS ARRANGED BY STATIONARY PHASE

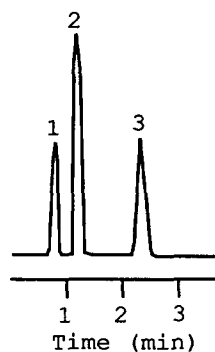| Stationary phase[a] | $\dfrac{k'_{\text{Ethylene oxide}}}{k'_{\text{Hydrogen sulfide}}}$ | $\dfrac{k'_{\text{Carbonyl sulfide}}}{k'_{\text{Carbon dioxide}}}$ | $\dfrac{k'_{\text{Carbon dioxide}}}{k'_{\text{Nitrous oxide}}}$ |
|---|---|---|---|
| Silica gel | 0.94 | 1.37 | 1.11 |
| Epoxy | 1.16 | 1.55 | 1.03 |
| CBI | 1.29 | 1.84 | 0.99 |
| CBI AC | 1.33 | 1.86 | 0.99 |
| CBIII | 1.32 | 1.84 | 0.98 |
| HIGH | 1.35 | 1.75 | 0.99 |
| CBIII AC | 1.34 | 1.87 | 1.00 |

[a] See Table I or text for indication of phases.

Fig. 1. Isothermal GSC separation of a three-component noble gas mixture at 25°C on the directly bonded β-cyclodextrin (HIGH) stationary phase. Peaks: 1 = neon; 2 = argon; 3 = krypton.

and 1.87 on the acetylated α-cyclodextrin column (CBIII AC) (Table III). The acetylated cyclodextrins, while having smaller capacity factors, effectively retain the same separation factors (α) as the native cyclodextrins for many of the compounds in this study.

Fig. 1. shows the selectivity of the directly bonded β-cyclodextrin column (HIGH) for the noble gases. Neon, argon and krypton are all more than baseline resolved at 25°C and in under 3 min. Fig. 2 displays the separation of hydrogen, nitrogen, carbon monoxide and ethylene oxide on directly bonded β-cyclodextrin at three different initial temperatures of 20, 0 and −20°C. The first peak, hydrogen, produces a negative signal since it has a higher
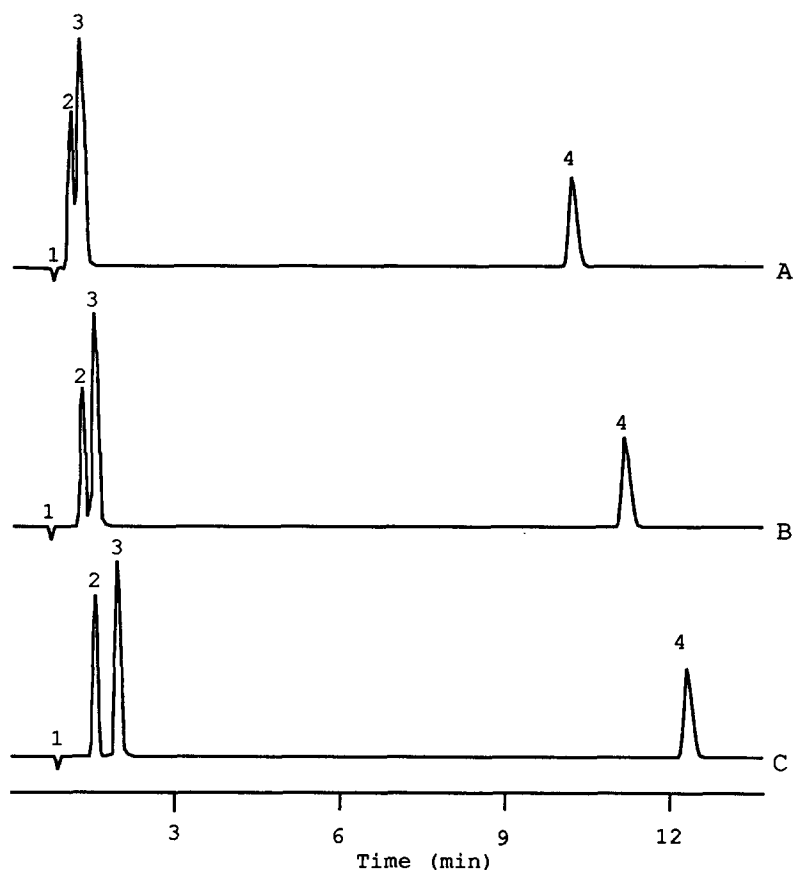


Fig. 2. GSC of a four-component gas mixture on directly bonded β-cyclodextrin. (A) initial temperature 20°C; (B) initial temperature 0°C; (C) initial temperature −20°C. The temperature program was: initial temperature for 2 min and ramp at 10°C/min until ethylene oxide eluted. Peaks: 1 = hydrogen (negative peak); 2 = nitrogen; 3 = carbon monoxide; 4 = ethylene oxide.
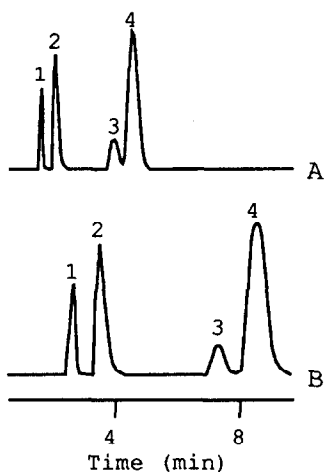
Fig. 3. Isothermal GSC separation of a four-component gas mixture on directly bonded β-cyclodextrin stationary phase. (A) −30°C; (B) −50°C. Peaks: 1 = nitrogen; 2 = carbon monoxide; 3 = methane; 4 = krypton.

thermal conductivity than the helium carrier gas. This separation is commercially important and currently requires two separate columns [36]. Fig. 3
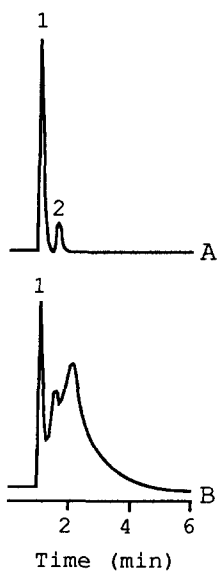


Fig. 4. Isothermal (135°C) GSC separation of nitrogen dioxide. (A) On silica gel; (B) on the directly bonded β-cyclodextrin stationary phase (HIGH). Note that the two overlapping peaks are obtained for nitrogen dioxide only on HIGH. Peaks: 1 = nitrogen; 2 = nitrogen dioxide.

presents the isothermal separation of nitrogen, carbon monoxide, methane and krypton (elution order) at temperatures of −30 and −50°C. These separations can be achieved closer to or at room temperature with the use of a longer column. The elution order of krypton and methane on a molecular sieve 5A column is the opposite of that obtained on the directly bonded β-cyclodextrin phase [18].

Fig. 4B shows an unusual chromatogram obtained for nitrogen dioxide when analyzed on the directly bonded β-cyclodextrin column, compared with the same compound chromatographed on silica gel (Fig. 4A) or any other column used in this study. Why this particular column produces two overlapping peaks for nitrogen dioxide while all other columns produce a single peak is unknown. Rechromatographing either peak from the HIGH column on a silica gel column gives a single nitrogen dioxide peak. It appears that the peak overlapping with nitrogen dioxide may be dinitrogen tetraoxide. However, we have no good explanation as yet for its appearance under these particular conditions.

Cyclodextrin bonded to a silica gel support and used as a GSC stationary phases is shown to be useful in the separation of many inorganic gases. Unique selectivities for some compounds have been observed. The selectivity differences between silica gel and the cyclodextrin phases can be attributed partially to modified support polarity. In addition, the native cyclodextrin moiety allows for both polar interactions with the hydroxyl groups and non-polar interactions with the cavities. Continued research on cyclodextrins as GSC stationary phases will very likely provide a more selective and widely useful column for the separation of gases and volatile compounds. We are now attempting to perfect an equivalent open-tubular capillary column for these separations.

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