

## Chapter 2

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# *Silica-Based Solid Phase Extraction*

Estimates have shown silica gel to be the base material for 90% of extraction columns manufactured. The other 10% of materials used for SPE are alumina, carbon, Fluorosil®, and synthetic polymers.

Synthetic polymers include polystyrene divinyl benzene (PSDVB), polystyrene divinyl pyrrolidone (PSPVP), and dimethyloxymethyl naphthalene divinyl benzene (DMN-DVB), and mixtures of these compounds to obtain the desired characteristics.

Silica gel is an amorphous, highly porous, partially hydrated form of silica ( $\text{SiO}_2$ , a substance made from the two most abundant elements on earth, silicon and oxygen). In fact, 55% of the earth's surface consists of either silica (silicon dioxide) or silicates (silica combined with metal oxides). Most of the silica found naturally is not significantly hydrated and can be in crystalline or amorphous forms. It is a simple material to characterize chemically and physically.

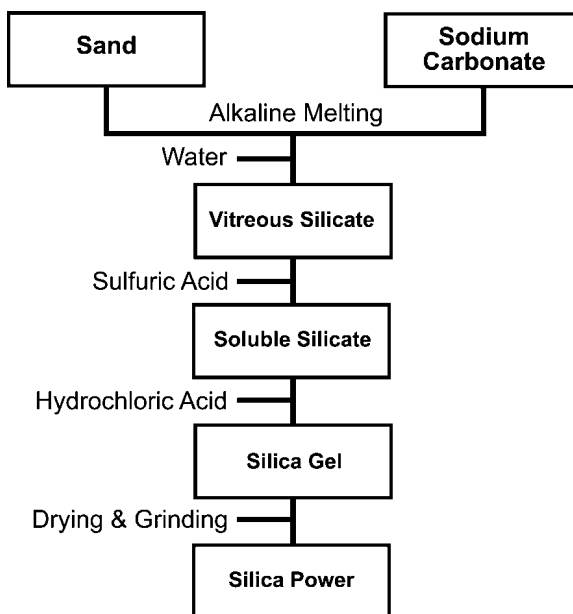
Silica gel has a number of distinctive properties that make it an ideal base material. It is easily made, at minimal cost, and is uniform in its properties. Silica gel has a rigid backbone, which shows little if any swelling or shrinking in a broad range of solvents. It can be cleaned easily prior to use for high-sensitivity work. Ion-exchangers on silica backbones recover quickly from changes in pH or solvent types. The hydroxyl groups on silica allow a large variety of different functional groups to be added for increasing selectivity. These various characteristics have a significant impact on how well the bonded phase packing performs as an extraction device.

The silica used for SPE extraction columns is essentially porous and noncrystalline, with the general formula  $\text{SiO}_2 \times \text{H}_2\text{O}$ . Water is chemically available in nonstoichiometric amounts, forming the silanol groups ( $\text{SiOH}$ ). The silanol groups are the polar groups through which other organic moieties are bonded. We will discuss the unique properties of the silanol groups in detail later in this chapter.

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**Fig. 1.** Manufacture of Silica.

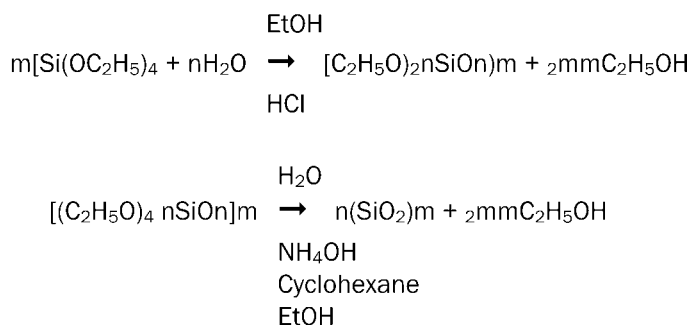
Amorphous silica gel does not carry the same hazard of silicosis encountered with crystalline silica. Even though the silica is nonhazardous, when working around any product that may be suspended into the air, analysts are advised to use proper respiratory protection, especially when working with particles 10  $\mu\text{m}$  size or smaller.

The safe working pH range of silica is 2.0 to 9.0. Below pH 2.0, Si-C bonds of derivatized material can be cleaved; above pH 9.0, silica is slowly solubilized into silicate.

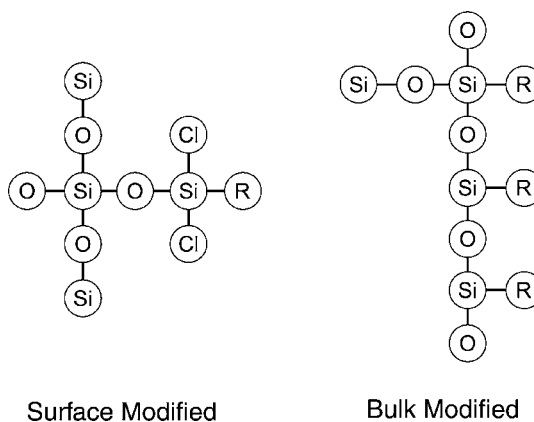
The kinetics of the dissolution of silica are slower at atmospheric pressure than at the high pressures used in HPLC, and the residence time of any elution solvent is measured in terms of minutes, not hours. Therefore, the dissolution of silica gel is not a problem in SPE as it is in HPLC. If you are getting a white precipitate you may want to check your preliminary column wash to see if it is strong enough to remove any unbound polymers from the column. Also check to see if you have buffer salts that may be insoluble in your elution solvents.

## 2.1 THE MANUFACTURE OF SILICA GEL

Silica gel has been manufactured by a variety of methods. It was originally made from sand by alkaline melting with sodium carbonate to produce sodium silicate solution. On standing under controlled conditions, sodium silicate solution will form silica gel (Figure 1). This process is termed the Patrick process (1919) and was developed by the US Army after World War I to produce commercially an inexpensive replacement or addition to the charcoal adsorbent in gas masks.



**Fig. 2.** Synthesis of high-purity silica gel.



**Fig. 3.** Modified silicas.

The current method for the synthesis of high-purity (i.e., chromatographic grade) silica gels includes the polymerization of tetraethoxysilane to form silica gel molecules (Figure 2). By introducing additional alkoxy silanes into the polymerization process you can create bulk-modified silicas where the bonded phase is polymerized not just on the surface but also throughout the silica copolymers (Figure 3).

## 2.2 SILANOL GROUPS

Silanol (Si-OH) groups must cover the surface of the silica for the silica to be useful for the preparation of SPE materials. The silanol groups are the points of attachment for the bonding of various chemistries onto silica. Figure 4 shows several different types of silanols available for bonding. Amorphous silica, with its porous, highly disordered structure, bears all three types of silanols (Figure 5).

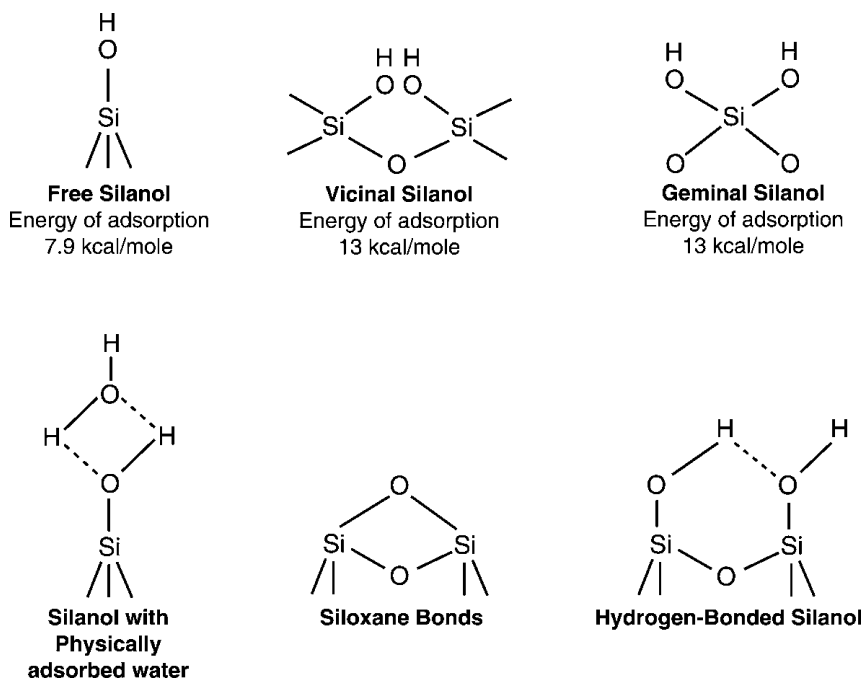


Fig. 4. Types of silanols on silica.

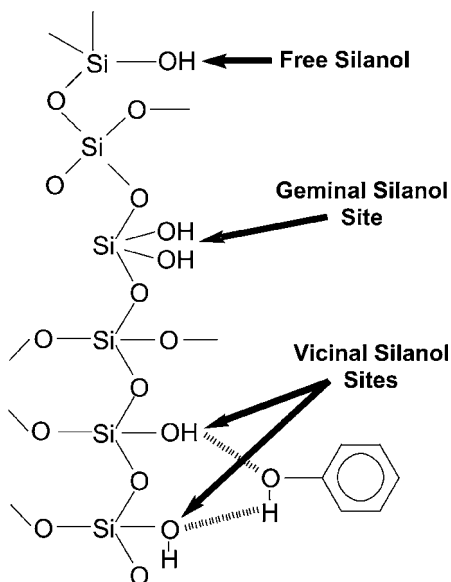


Fig. 5. Amorphous silica with all three types of silanol groups.

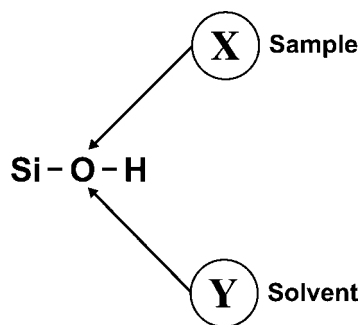


Fig. 6. Silanol and analyte interaction on silica.

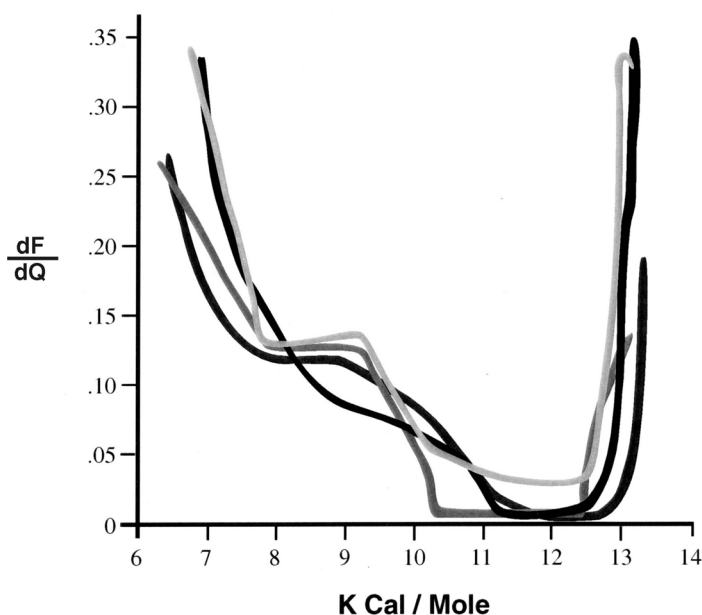


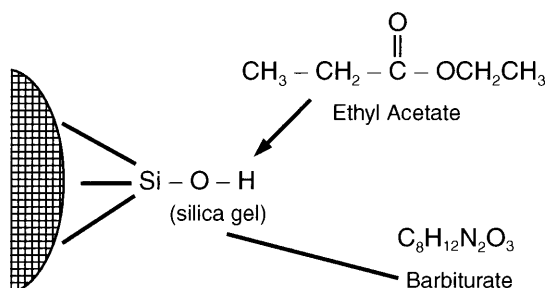
Fig. 7. Energy of adsorption on silica gel.

The silanol concentration of completely hydroxylated silica is about  $9/\mu\text{mol}/\text{m}^2$ . Because of steric considerations, only about 50% of these can be bonded, giving a maximum bonding density of about  $4.5 \mu\text{mol}/\text{m}^2$ .

The silanol group can absorb compounds onto the silica surface by hydrogen bonding (Figure 6). A free silanol group has energy of absorption of 7.9 kcal/mol. Geminal and vicinal silanol groups have energies of absorption of 13 kcal/mol (Figure 7). The strong energies of absorption for these groups leads to strong, sometimes irreversible bonding of compounds onto the silica surface. This factor limits the effectiveness of raw silica as a sorbent, especially for normal phase separations. Bonded phase sorbents are able to limit the silanol group interactions of the silica backbone by attaching a blocking group commonly referred to as an endcap. Table 1 shows a summary of characteristics of silica gel that make it so viable for use in SPE.

**Table 1**  
**Summary of Bonded Phase Packing**

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- Most SPE column packings use silica gel as a backbone.
  - Silica ( $\text{SiO}_2$ ) is essentially porous and noncrystalline (amorphous).
  - Silica gel has hydroxyl groups termed silanol groups.
  - Silanol groups are the polar groups through which other functionalities can be attached.
  - The nature of silanols has a direct effect on extractions.
  - Free hydroxyl groups have an energy of absorption of 7.9 kcal/mol.
  - Vicinal and geminal silanols have high energies of absorption (>13 kcal/mol), which may lead to irreversible adsorption.
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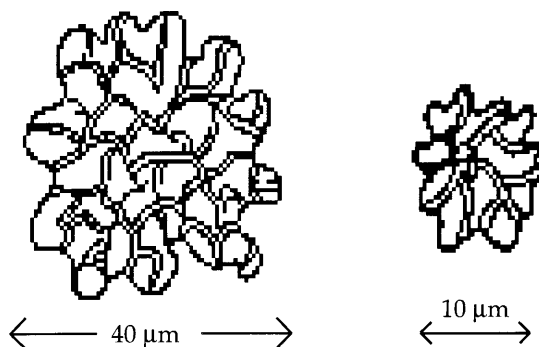
**Fig. 8.** Silica gel shapes and adsorption, liquid/solid.

The primary differences seen in recovery in many SPE sorbents can be attributed to the effectiveness of the endcapping process. The most efficient bonded phase is one that has the minimum number of hydroxyl groups unreacted and, consequently, the maximum surface coverage. Owing to the steric hindrance from the bonded moiety itself only a proportion of the silanol groups can be bonded, and there was little that could be done in the past to avoid this problem. Current technologies have overcome this problem and there are encapped packings available now that exhibit negligible absorption due to free hydroxyls. Keep in mind, however, that this does not eliminate minor absorptive effects due to the oxygen in the siloxane structure ( $\text{Si-O-Si}$ ). Figure 8 shows the hydroxyl site on the adsorption column.

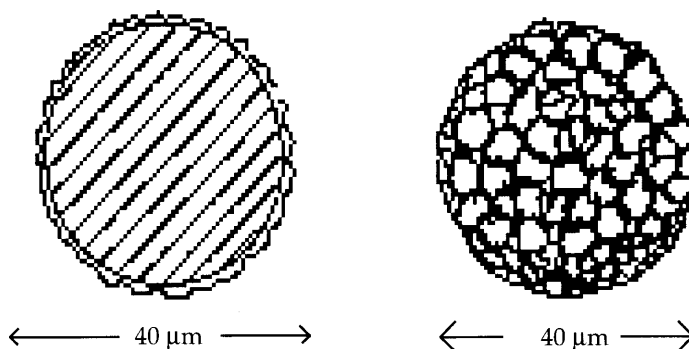
### 2.3 SILICA GEL SHAPES AND SIZES

Silica comes in two basic shapes: irregular (Figure 9) and spherical (Figure 10). For the purposes of bonded phase extraction, there appear to be no significant differences between irregular particles and spherical particles. These terms are basically self-defining.

Silica also comes in two consistencies: porous and pellicular. Porous silicas are used most frequently in SPE because of their high surface area and capacity. In porous silica up to 97% of the surface can be internal, leading to a large amount of surface area. Pellicular silicas (ones with solid cores and porous surfaces) are used predominantly in HPLC because of their efficient mass transfer capability.



**Fig. 9.** Irregular silica particles of 40  $\mu\text{m}$  and 10  $\mu\text{m}$ .



**Fig. 10.** Pellicular and porous spherical silica particles of 40  $\mu\text{m}$  diameters.

**Table 2**  
**Particle Size and Pore Diameter**

Silica shape	Particle range ( $\mu\text{m}$ )	Pore diameter (in $\text{\AA}$ )	Type of application
Irregular	5–20	60	Analytical SPE SPE Preparative Process
	40–60	60	
	60–90	60	
	90–125	60	
	120–200	60	
Spherical	5	120, 200, or 300	
	10	120, 200, or 300	
	15	120, 200, or 300	
	15	120, 200, or 300	
	25	120, 200, or 300	
	50	120, 200, or 300	

Diatomaceous earth (diatoms) is a natural source of silica and has been used in earlier forms of sample cleanup techniques.

All silicas used in contemporary SPE are synthetically manufactured and available in a variety of particle sizes and pore diameters. Table 2 shows particle size distributions and pore diameters for irregular and spherical silicas.

## 2.4 *PARTICLE SIZE*

Particle sizes directly affect the flow characteristics of a SPE column and attention must therefore be given to both the average particle size and the particle size distribution.

The average particle size for most SPE columns is between 40  $\mu\text{m}$  and 60  $\mu\text{m}$ . Smaller particles do not improve the extraction efficiency. Larger particles give better flow characteristics but there have been reports that recoveries may drop off at lower sample concentrations. At the present time it has not been determined whether this is due to the larger particles or the increased flow rate that accompanies them.

In addition to the average particle size, the particle size distribution is an important consideration in SPE. It would be ideal if every particle in the tube had exactly the same particle size and composition; however, the economics of accomplishing this would make it impractical. Therefore, the particles in SPE columns are of various sizes. Even if the reported particle size is 50  $\mu\text{m}$  the actual particle sizes may be anywhere between 5  $\mu\text{m}$  and 100  $\mu\text{m}$  depending on how well the material is processed. The narrower the particle size ranges, the better the consistency flow from column to column. Fine particles, or “fines” (i.e., particles smaller than the actual distribution), will increase resistance to flow, whereas larger particles may reduce the efficiency of extraction.

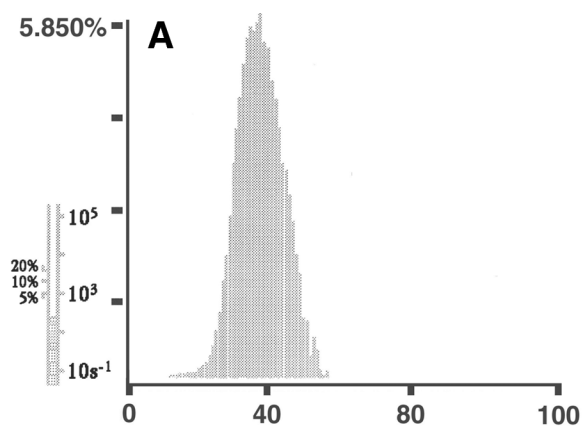
Figure 11 A–C illustrates particle size analysis of several silica gels using a Coulter multisizer analyzer. Silica gel A has a distribution centered around 36–40  $\mu\text{m}$ . This is a relatively narrow cut with very few smaller (fines) or larger particles. Silica gel B has a larger mean value, at 60  $\mu\text{m}$ . This silica has no fines or larger particles. Silica gel C has a distribution centered on 50  $\mu\text{m}$ . Notice the amount of larger and smaller particles outside the distribution. The relatively small number of larger particles will not affect the efficiency of the extraction. The smaller particles (fines) may clog the frits and impede sample flow through the column.

Another concern is that the process of automating column packing may affect the actual particle distribution of the final product. Figures 12 and 13 illustrate the particle size distribution during the steps of automated packing in a machine. Note that the particle distribution was fractured on the final step (placing of the frit on the top of the SPE column). This particular batch of columns had flow problems.

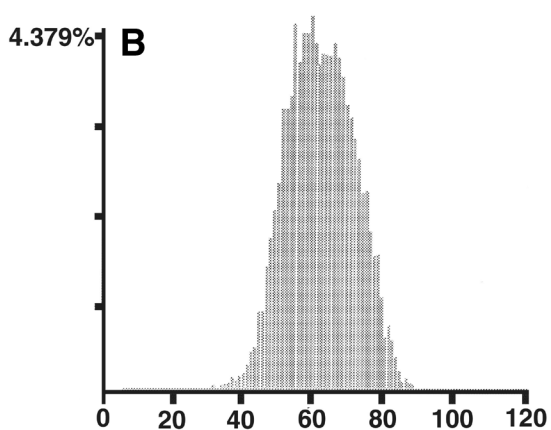
## 2.5 *SURFACE AREA OF SPE SORBENTS*

The surface area of a porous solid is equal to the sum of its internal and external surface areas. The external surface area corresponds to the geometric surface of particles per gram of silica. In general, the surface area of silica tends to vary inversely with the pore size, so that the larger the pore size, the smaller the surface area. The surface area of silica used for SPE ranges from 400  $\text{m}^2/\text{g}$  to about 550  $\text{m}^2/\text{g}$ .

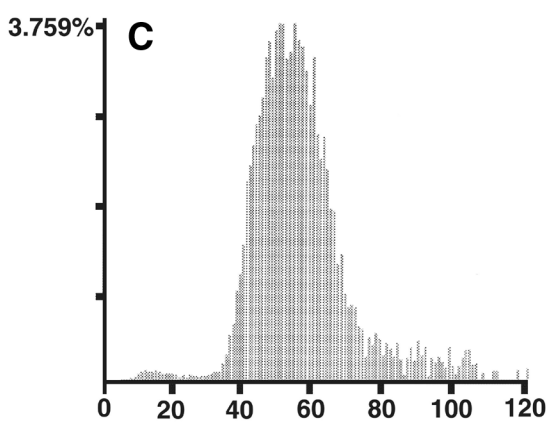




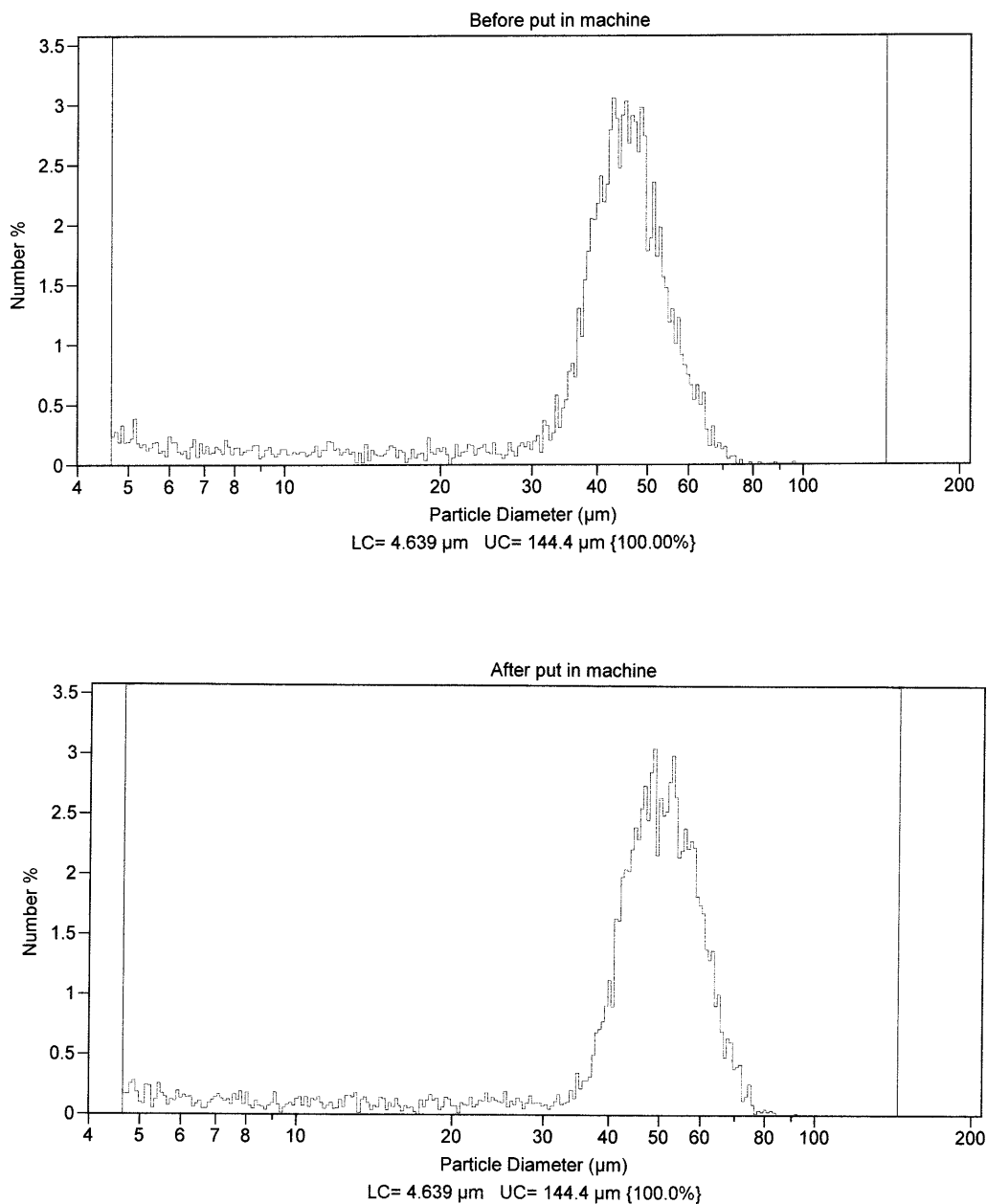
**Fig. 11A.** Particle size distribution silica gel A.



**Fig. 11B.** Particle size distribution silica gel B.



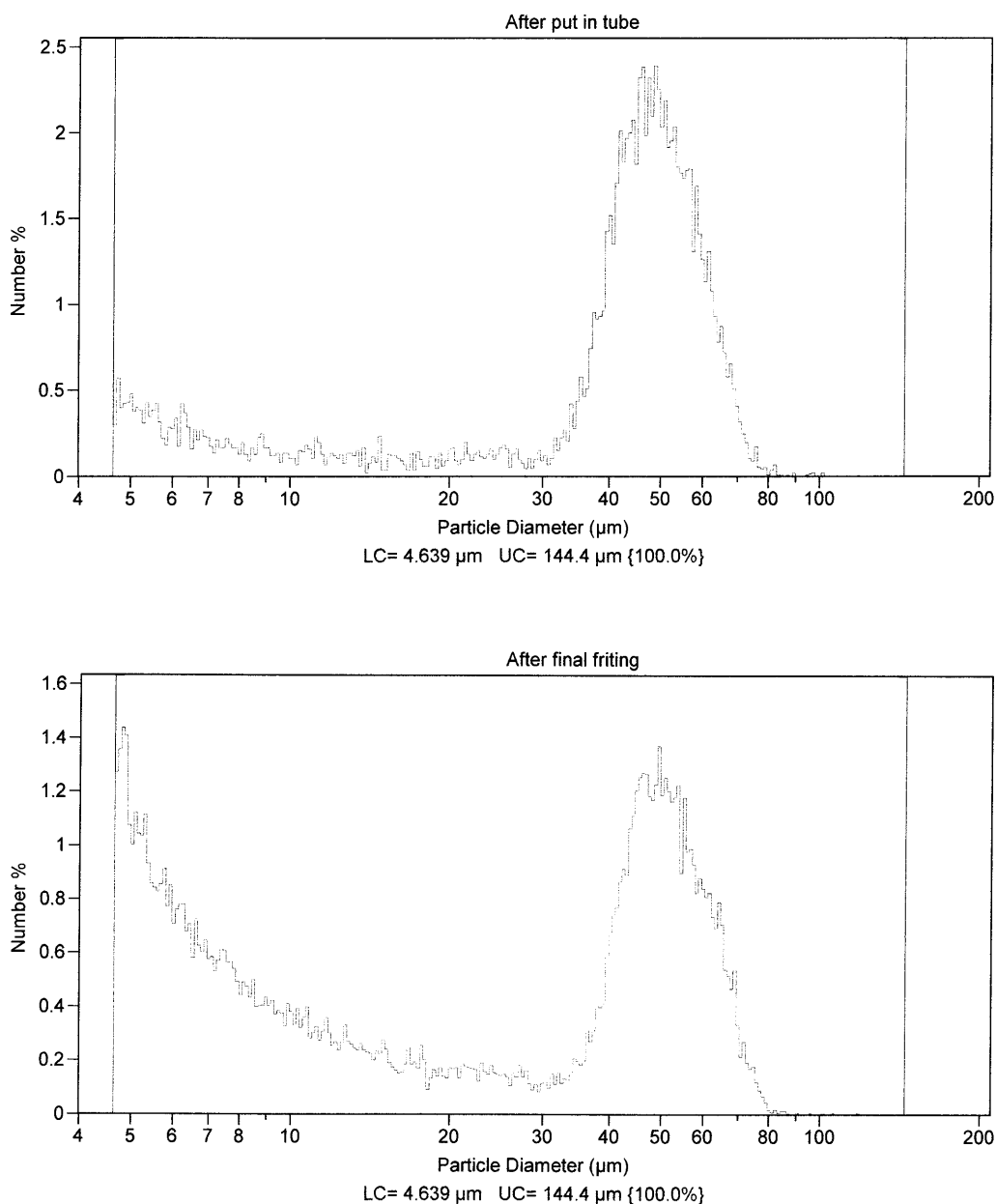
**Fig. 11C.** Particle size distribution silica gel C.



**Fig. 12.** Particle size analyses of silica before and after it was added to an automatic filling machine.

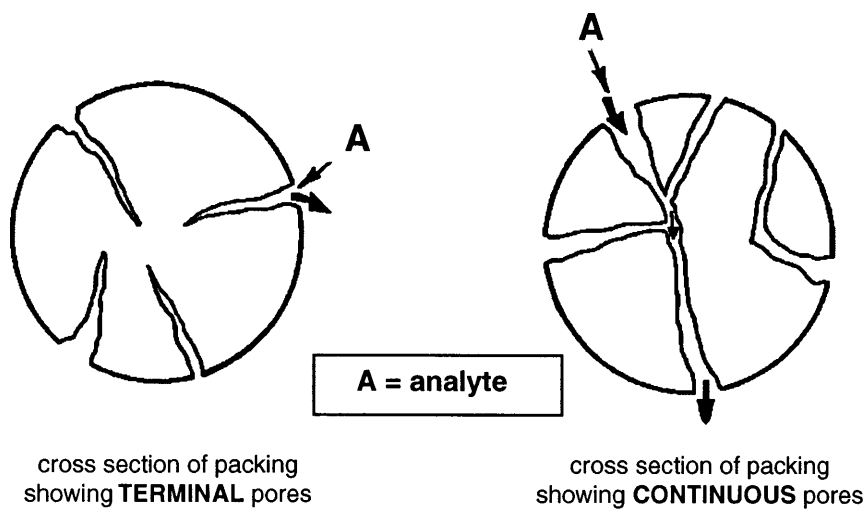
## 2.6 POROSITY

A pore is a cavity or channel connecting with the surface of a solid. Figure 14 shows two types of pores that connect with the surface. The spaces or interstices between particles are voids rather than pores. A pore that does not connect with the surface is

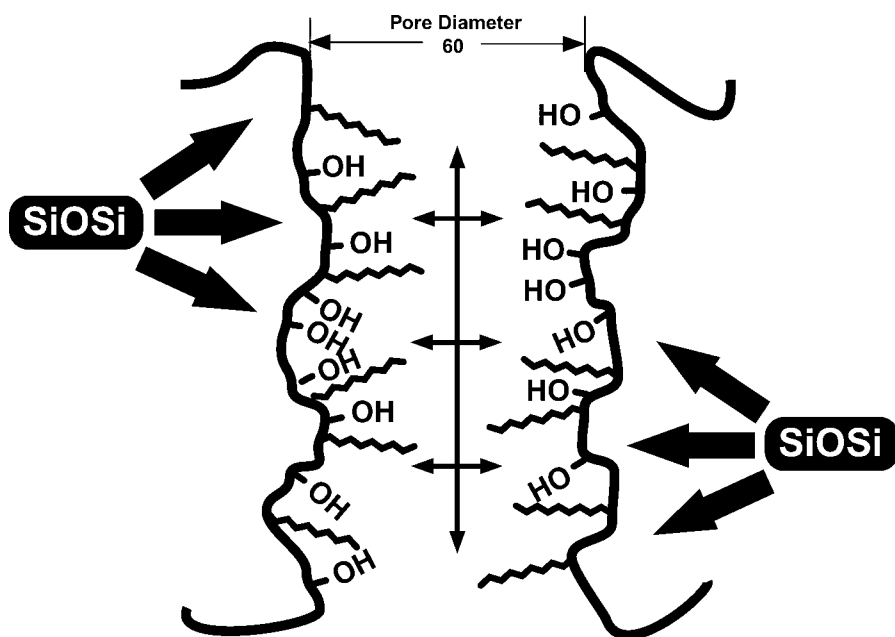


**Fig. 13.** Particle size analyses of silica as it was filled into tubes by an automatic filling machine.

called a closed pore or an internal void and will not contribute to the porosity or specific surface area. Pores that connect with the surface at one location are called terminal pores. Pores that connect on the surface at two or more locations are called continuous pores. Continuous pores exhibit better mass transfer than terminal pores (Figure 15).



**Fig. 14.** The difference between continuous and terminal pores.



**Fig. 15.** The internal surface of a continuous pore.

More than 97% of the specific surface area is internal surface area because of the pores. Therefore, the particle diameter has little importance with regard to the surface area. The surface area of silica gels depends mainly on the pore size and pore volume.

Pore sizes cover a range of several orders of magnitude. The average pore size diameter useful for SPE is 60 Å. Pores of 100 Å seem to work as well. The advantage of larger-size pores for SPE has not yet been demonstrated, and manufacturers of silica gel have not been able to consistently manufacture reproducible pore diameters of 50 Å.

## 2.7 METAL CONTENT OF SILICA GEL

Silica gel contains impurities on processing. These impurities include alkali metals, calcium, magnesium, and trivalent metals such as alumina and iron (1).

Although small amounts of these impurities can be tolerated, their levels must be carefully controlled. Metal ions present on the silica surface at trace levels can form sites of nonspecific absorption with high activities. These sites also may facilitate the dissolution of silica when it comes into contact with solvents. A significant source of metals may be in the grinding of the silica gel to smaller particles. In most cases the manufacturing process will reduce the metal content of the bonded silica.

## REFERENCE

<sup>1</sup>Hocky, J. Chem Indust. Jan. 9: 57, 1965.





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