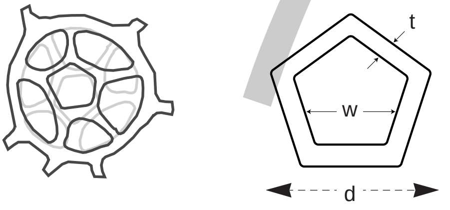
1. CELL STRUCTURE

A foam consists in a large number of interconnected cells, forming a cellular network. The cell is the basic unit of the foam ; its morphology and the chemical composition of the struts both define the final properties of the foam. The study of the cell is therefore a key approach to develop and design new foams according to given specifications and requirements.

The cell is a dodecahedron, constituted by 12 windows (pentagon shape) and 30 struts :



The properties of the foam depend on the properties of each individual cell, in particular :

1) The nature of the polyurethane elastomer itself, which constitutes the struts
2) The thickness of the struts (t)
3) The overall size of the cell (d)
4) The size of the window, which is the size of the opening itself (w)
5) The presence of residual membranes in the window and their thickness
6) The anisotropy of the structure and the morphology (shape) of the cell

The foam remains a complex assembly of an elastomer and air, in which all these parameters are interdependent.

1.1 <u>The nature of the PU polymer :</u>

The struts are made of polyurethane elastomer. The nature of the elastomer influences directly the properties of the struts, such as the hardness, the elasticity, the fatigue, the UV resistance, the chemical resistance.

Some examples :

- The hardness and elasticity are influenced by the crosslinking level of the polymer, depending on the formulation type and the concentration of reactive sites in the basic raw materials.

- The UV resistance is mainly influenced by the chemical nature of the isocyanate and by the anti-oxydants or UV additives.

- The chemical resistance is mainly influenced by the nature of the polyol. Polyester polyol based foams are sensitive to water, while less sensitive to organic solvents. The contrary is noticed for polyether polyol based foams.

1.2. Struts thickness, overall cell size, size of the window, foam density :

Struts thickness, overall cell size, size of the window and foam density are related.

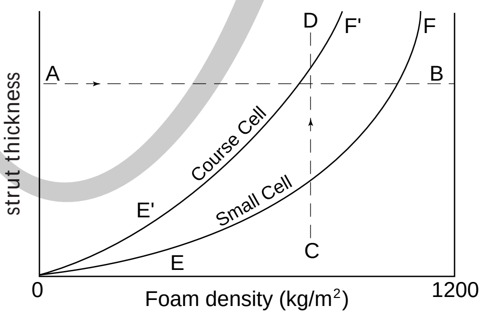
- When the overall cell size is constant, an increase of the foam density leads to an increase of the thickness of the struts, but to a decrease of the window opening and air content in the foam.

If	Overall cell size 1	=	Overall cell size 2
	Density 1	<	Density 2
Then	Thickness of strut 1	<	Thickness of strut 2
	Opening window 1	>	Opening window 2
	Air content 1	>	Air content 2

- For a given density, the decrease of the overall cell size leads to a decrease of the thickness of the struts, but the air content in the foam is the same.

If	Density 1	=	Density 2
	Overall cell size 1	>	Overall cell size 2
Then	Thickness of strut 1	>	Thickness of strut 2
	Opening window 1	>	Opening window 2
	Air content 1	=	Air content 2

The relation can be summarized in a graph.



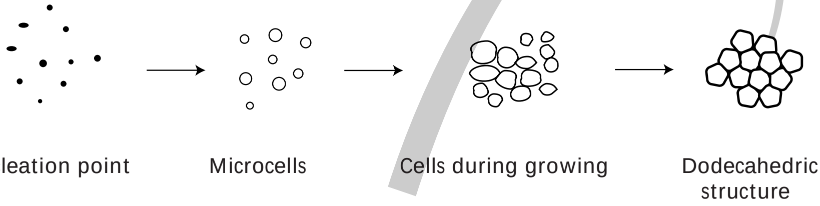
The graph can be interpreted from A to B (simultaneous increase of density and decrease of the overall cell size at constant thickness of the struts), from C to D (simultaneous increase of the thickness of the struts and increase of the overall cell size at constant density) and from E to F (or E' to F') (simultaneous increase of density and increase of the thickness of the cell struts at constant overall cell size) ;

At density 1200 kg/m³, i.e. approximately the density of the full elastomer, the thickness of the struts becomes "infinite". In reality, there is no cell anymore ... and also no struts.

1.3. Residual membranes :

The blowing reaction, i.e. the formation of the cellular structure itself - starts from nucleation points which become the future individual cells.

At each nucleation point, gas molecules are formed. These nucleation points become “microcells”, which will increase in volume. Spherical at the beginning, the cells will reach a dodecahedric structure at the end of the foaming process :



During these steps, the cells are closed volume, otherwise the gas would escape and the foam would not grow anymore. It is a “condition sine qua non” of the foaming process. However, at the end of the foam rise, the membranes of the windows blow open - at least partially. This is an essential step in the production of flexible foam ; if the cells remain closed, the foam would shrink during the cooling. We have to remember here that the foam formation is an exothermic process and that the temperature inside the fresh foam can easily reach 150°C. During the cooling, the gas which would remain encapsulated in a closed cell, would exert a depression force, leading to the contraction of the cell, and the shrinkage of the foam.

Therefore, fresh flexible foam always contains open windows. The ratio between closed and open windows affects the physical properties of the foam, such as the air permeability, the hardness at the first compression, the acoustical performance.

1.4. Anisotropy :

The foaming process is a “free rise” process. The foam expends the fastest in the easiest direction, which is in the case of one shot process, in the vertical direction. The shape of the cell, instead of being spherical, is elliptical (circle and ellipse are defined as an overall approximate shape ...).

The shape of the cells can be visualized in the vertical section of the block.

Following this theory, the cross section of an individual cell would vary, depending of the section angle, from a circle to an ellipse with the maximum excentricity.

At angle 0 (vertical cutting)	:	ellipse with maximum excentricity
At angle 90° (horizontal cutting)	:	circle

The small diameter of the ellipse is constant (and could be the standard to define the cell size) and identical to the diameter of the circle.

The anisotropy of the foam is the variation of the shape of the cell in function of the cutting angle. It is an important parameter, which has not been enough investigated. It is quite evident that the mechanical properties of each single cell - like the hardness, elongation - depend on the anisotropy. Therefore, the overall properties of the foam also depend on the cutting direction.

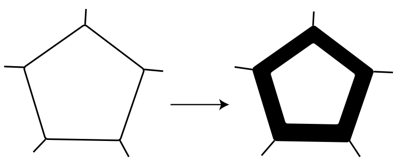
1.5. Modification of the cell :

The cell morphology can be further modified, either by reticulation, impregnation or by heat compression.

a) Reticulation :

It is the thermal process which melts all the residual “windows”. The morphology of the foam remains the same (the struts become a little thicker), but the air permeability increases substantially due to the complete opening of the tri-dimensional cell structure.

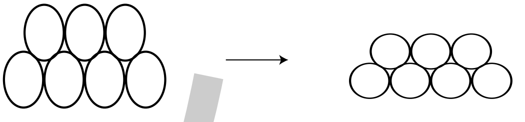
b) Impregnation :



By impregnation, the overall dimension of the cell remains the same ; the window opening becomes smaller, the struts become thicker, and the overall density of the foam increases, due to the extra coating material of the visual PU struts.

c) Heat Compression :

By heat compression, the cells are reduced and horizontally deformed.



The density of the foam increases, while final cell size decreases. As a result, air permeability decreases and the capillarity increases !

1.6. Air content :

The total weight of polyurethane foams, F, per cubic meter, is the sum of the weight of the polyurethane elastomer, U, and the air, A.

$$F = U + A$$

The weight of the air is very small towards the weight of urethane elastomer and can be considered as zero value. Therefore :

$$F = U$$

It only means that a foam, for example, of 30 kg/m^3, contains 30 kg of polyurethane elastomer per m^3. The density of a polyurethane elastomer is approximately 1200 kg/m^3.

Therefore, the real volume, V, occupied by the elastomer, is :

$$V = U / 1200$$

For a foam of 30 kg/m^3, the volume occupied by the elastomer is 30 kg/1200 kg/m^3 = 0.025 m^3. The volume occupied by the air is therefore (1 - V), which, in case of a foam of 30 kg/m^3, is 0.975 m^3.

The relation is therefore :

Content of air in % volume =

$$(1 - V) * 100 = (1 - U/1200) * 100 = (1 - F/1200) * 100$$

Example :

Foam density (kg/m^3)	Content of air (%)
10	99.2
20	98.3
50	95.8
100	91.7
300	75.0

1.7. The cell size unit :

The cell count is actually expressed in number of cells per linear cm or in PPI (number of pores per linear inch).

In reality, the definition is confused because the cell is a volume (tridimensional unit), which is reduced, by visual inspection, to a one-dimensional value. Moreover, the volume of each individual cell presents a high dispersion. To properly characterize a foam, 2 parameters should be mentioned :

- The average volume of the individual cells, from which the number of cells per volume (per m^3) can be easily calculated.
- The dispersion of the volume of each individual cell.

Studies are going on on this subject.

1.8. The number of cells per m^3 :

This can be calculated from the average volume of each individual cell.
For example, the average volume of a cell of a 60 ppi foam is 0.2 mm^3 which means that such a foam contains 5 billions of cells per m^3.

The number of cells per m^3 for different ppi value is :

PPI	Number of cells/m^3
90	Approx. 17,000,000,000
60	Approx. 5,000,000,000
30	Approx. 600,000,000
10	Approx. 20,000,000