

# Pneumacel: Basic Technology and Applications

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## Synopsis

Pneumacel, a new kind of resilient closed-cell foam, has characteristics especially useful for firm cushioning materials. A fluorocarbon inflatant in addition to air present in the closed cells provides a mechanism for recovery from long-term loading for nonelastomeric polymer foams such as poly(ethylene terephthalate). The basic structural features characterizing pneumacel contribute to its performance as a resilient foam. Important principles in selecting the optimum combination of polymer and inflatant are described, as well as the process for making pneumatic cellular products. Development work on applications of pneumacel fibers has led to its utilization in cushions for under carpets, padding for use over springs in mattresses, automobile seats, and furniture. Properties of the assemblies of fibers for such uses are described.

## INTRODUCTION

Pneumacel is a new kind of resilient closed-cell foam which is remarkable for combining low density and high flexibility in a firm cushioning material. Its small closed cells are inflated to about 1.3 atm pressure, with about 0.3 atm of a slowly permeating fluorocarbon in addition to the 1 atm of air present at equilibrium. The slowly permeating inflatant is important to pneumacel because it provides the principal mechanism for recovery from long-term heavy loading. In this respect, pneumacel differs from all other resilient cushioning materials. Flexible polyurethane foams and foamed rubbers are not pneumatic because they have open cells. They recover from load because the elastic polymer itself tends to return to its original shape. In contrast, pneumacel is made not from elastomers, but from "hard" polymers such as nylon or poly(ethylene terephthalate), which have glass transitions well above room temperature. The cell walls are extremely thin and flexible and, because the foam density is only 0.02 g/cm<sup>3</sup>, the polymeric structure itself would have little tendency to recovery from long-heavy loading were it not that the closed cells retain the inflatant. When the load is removed, the inflatant gas assists recovery in two ways. First, the residual pressure of the inflatant causes some immediate recovery. Second, over a longer period of time, the osmotic gradient across the cell walls causes air, which was forced out over days or weeks under load, to permeate back in to reestablish an internal air pressure of 1 atm.

This reequilibration with air is a key property of this new cellular material. Figure 1 shows (1) a fully inflated pneumacel fiber before any external pressure was applied, (2) the same fiber after pressure had been applied, and (3) the same fiber 48 hr after the pressure had been removed. The development of a useful product from pneumacel depends on generating foams with a very high proportion of closed cells having walls which are not only strong and flexible but are also good diffusion barriers so that the inflatant is retained during the lifetime of the cushioning product.

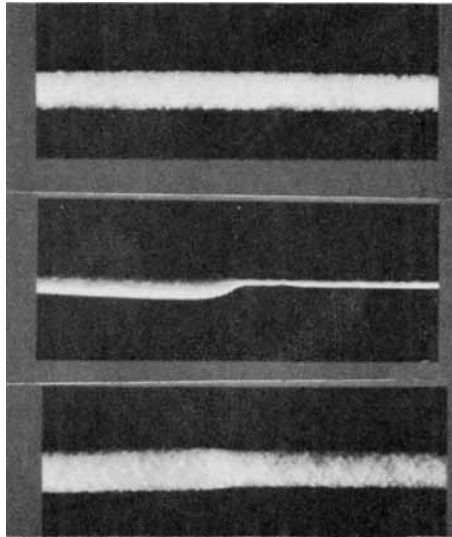


Fig. 1. Pneumacel fiber before any external pressure has been applied (top), after pressure has been applied (center), and 48 hr after the pressure has been removed (bottom).

### BASIC PROPERTIES

The five key structural features characterizing pneumacel and contributing to its high performance are listed in Table I. The first two relate to the toughness and flexibility of the foam. "Uniform distribution of polymer" means that the cell walls are uniform in thickness and that there is little or no extra polymer in fillets at the intersections of the cell walls. Figure 2 shows a section of pneumacel from poly(ethylene terephthalate) magnified about 5000 $\times$  taken with a transmission electron microscope. The thinness of the walls and the absence of extra polymer at the cell wall intersections is shown. Figure 3, a section of similar polyester pneumacel taken with a scanning electron microscope at slightly lower magnification, shows the typical polyhedral cells of a low-density foam. The average cell is approximately 25  $\mu\text{m}$  in diameter.

Uniplanar orientation of the crystallites, the fourth key property of pneumacel, means that two axes of the unit crystal lie preferentially in the plane of the cell wall. This is illustrated in Figure 4 by using ordinary bricks as models for polymer crystallites. A brick has three unequal axes. Uniplanar orientation

TABLE I  
Structural Features of Pneumacel

Crystalline polymer
Walls < 2 $\mu\text{m}$
Uniform distribution of polymer
Uniplanar orientation
Uniform texture

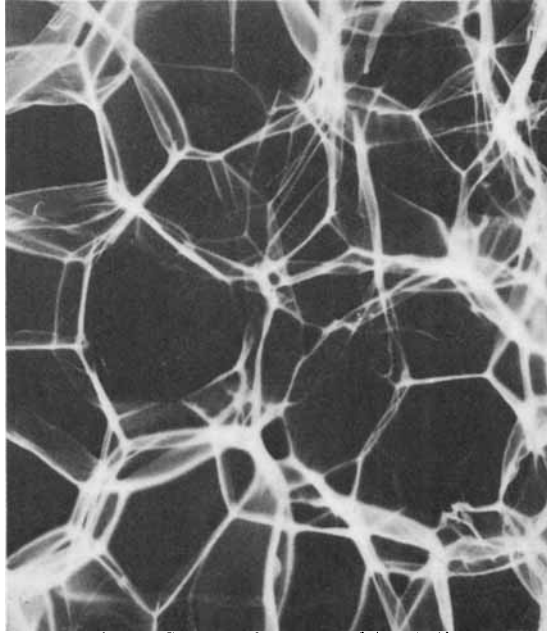


Fig. 2. Section of pneumacel ( $\times 5000$ ).

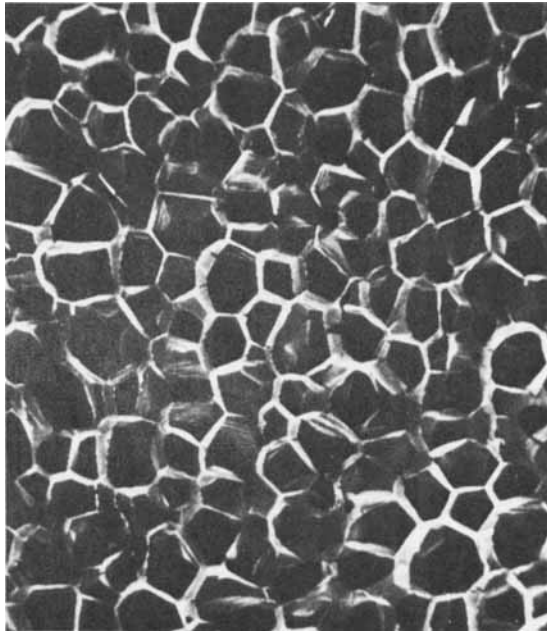


Fig. 3. Cross section by scanning electron microscopy.

of a group of bricks on the floor may be obtained by laying the two longest axes, the  $a$  and  $b$  axes in the diagram, parallel to the floor. The bricks may now be turned about the third ( $c$ ) axis; but so long as the bricks lie flat on the floor, they have “uniplanar” orientation. This special kind of molecular order can be measured by electron diffraction and is marked by the near or total absence of diffraction from spacings along the  $a$  and  $b$  axes.<sup>1</sup>

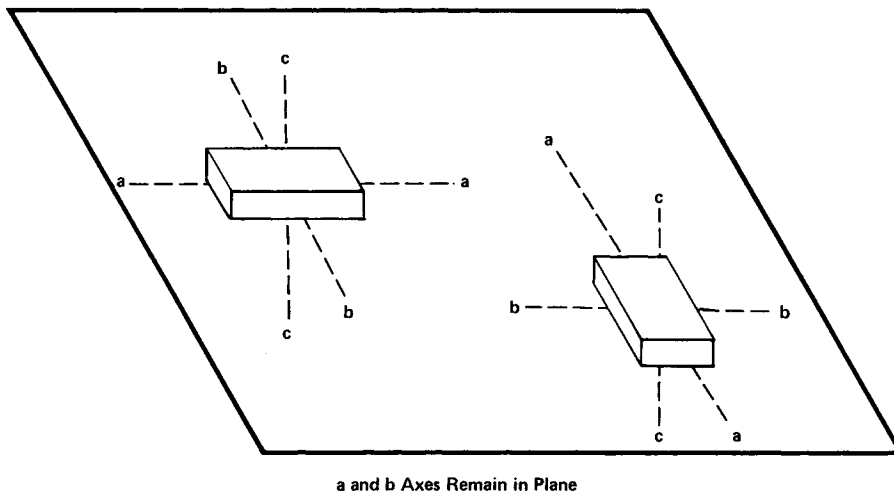


Fig. 4. Model for polymer crystallites.

The fifth characteristic of pneumacel is the uniform texture of the cell walls. This property can be measured with a polarizing microscope. A thin section of foam is prepared in such a way that a single cell wall can be examined in polarized light. Nonuniformities show up as lacy, cobwebby, or patchy light and dark areas. A pneumacel wall is uniform in brightness over its whole surface.<sup>2</sup> Retention of the inflatant, particularly during mechanical flexing, is related to the uniformity of cell structure and polymer morphology. For example, foams superficially similar to pneumacel may have nonuniformities visible in their cell walls under polarized light. Such foams lose resiliency during flexing because inflatant escapes through mechanically damaged cell walls. Two practical tests for evaluating the durability of inflated foam cushioning fibers are based on a static load of 200 psi for 1 week and a cyclic load of 25 psi for 8000 cycles, on 4 sec and off 4 sec. Each of these load tests is followed by a recovery period of a few days to allow reequilibration with air; the thickness recovery and the inflatant loss are then measured. These tests have proven quite useful, because they reflect the kind of loadings encountered in commercial applications like rug underlay: the 200 psi static load models a piano leg indenting a rug; the 25 psi cyclic load simulates a person walking.

The principles used in selecting useful combinations of polymer and inflatant are the same as those used in other areas in which gas permeability is important such as food packaging. Table II shows some published values of permeation coefficients<sup>3</sup> for some common polymers and gases. The lower ones on the chart, polyvinyl chloride, nylon, poly(ethylene terephthalate), and polyvinyl fluoride, make barriers to ordinary gases which are more than 100 times as effective as barriers of poly(chlorobutadiene).

There are other important considerations in selecting the polymer; for example, the cost of ingredients and whether a practical process can be devised for making useful foam from it. Another key point is the effect of water, to which any cushioning foam will be exposed at least occasionally. Polymers like cellulose, poly(vinyl alcohol), and nylon are more or less plasticized by water. This decreases the interchain molecular forces, increases the mobility of the polymer

TABLE II  
Permeability Coefficients of Gases Through Various Polymers<sup>a</sup>

	N <sub>2</sub>	O <sub>2</sub>	CO <sub>2</sub>
Poly(chlorobutadiene)	12	40	250
Polypropylene	4.4	23	92
Polyethylene (high density)	3.3	11	43
Poly(vinyl chloride)	0.4	1.2	10
Nylon 66	0.2	0.4	1.6
Poly(ethylene terephthalate)	0.05	0.3	1.0
Poly(vinyl fluoride)	0.04	0.2	0.9

<sup>a</sup> Units = cm<sup>3</sup> (STP) × cm<sup>-2</sup> (area) × cm<sup>-1</sup> (thick) × sec<sup>-1</sup> × cm<sup>-1</sup> (HgP) × 10<sup>11</sup>. Data from ref. 3.

molecules, and increases the permeation of gases. A few examples are shown in Table III.<sup>4</sup> Poly(vinyl alcohol) and cellophane are quite water-sensitive, and their permeability increases as they become swollen with water at high relative humidity (r.h.) Pneumacel made from nylon shows some inflatant loss during tests at very high r.h. The water-insensitive polymers do not change in permeability as humidity increases. Thus the polymers most attractive for practical cushioning are good gas barriers and are insensitive to moisture.

The selection of inflatant gases was approached using well-known principles. For example, the permeation coefficient  $P$  can be separated into two components—the diffusion coefficient  $D$  and the solubility  $S$ :

$$P = DS$$

Each of these should be as small as possible for the best retention of inflatant.  $D$  becomes small as the size of the diffusing molecule increases, and  $S$  becomes small as the difference in solubility parameters<sup>5</sup> between the inflatant and polymer increases. In addition, a useful inflatant must have a substantial vapor pressure at room temperature. The compounds which combine to the highest degree the properties of large molecular size, high volatility, and low solubility in ordinary polymers are the fluorocarbons and related molecules like sulfur hexafluoride.

TABLE III  
Increase in Permeation of CO<sub>2</sub> with Humidity

	Temperature, °C	r.h., %	$P, \times 10^{11}$
Poly(vinyl alcohol)	23	0	0.01
		84	52
		94	119
Cellophane	15	0	0.1
		95	10.5
Nylon 6	30	0	1.0
		44	1.7
		95	2.9

Data from Ref. 4.

## PROCESSES

In the process for spinning pneumacel fiber, a confined mixture of polymer and solvent is heated to form a homogeneous solution at a temperature above the normal boiling point of the solvent and a pressure at least autogenous. This gives a hot solution of polymer in a relatively low boiling liquid at relatively high pressure. This solution is extruded into a region of substantially lower pressure and temperature under conditions such that a large number of bubble nuclei exists at the exit of the extrusion orifice. The concentration of the solution is chosen such that vaporization of the volatile components rapidly cools the solution to the temperature at which the polymer solidifies and freezes in the molecular orientation produced by the rapid extrusion and expansion process. These events all occur within a small fraction of a second, i.e.,  $10^{-2}$  sec or less.

A liquid suitable for use in this process must have an unusual combination of properties: a boiling point at least  $25^{\circ}\text{C}$  and preferably at least  $60^{\circ}\text{C}$  below the melting point of the polymer; it should be substantially unreactive with the polymer during mixing and extrusion; the liquid must be a solvent for the polymer at the temperature, pressure, and concentration used for extrusion but a non-solvent below its normal boiling point; and it must form a solution which will undergo rapid vaporization on extrusion. Thus the polymer phase which is formed is quickly deplasticized so that it does not lose its high degree of molecular orientation after extrusion.

If increased bubble nucleation is desired, i.e., a larger number of smaller cells, lower boiling additives may be dissolved in the solution. These assist nucleation by lowering surface tension and increasing the pressure drop across the extrusion orifice. Although almost any soluble, low-boiling material is suitable, preferred materials are those which are supercritical above the polymer melting point. Useful additives include carbon dioxide, helium, methane, and Freon compounds. Finely divided solid particles can also be used.

Liquids or liquid mixtures suitable for use with a particular polymer can be uncovered by consulting the usual tables of physical properties for some of the criteria mentioned above. However, the unusual kind of solubility properties needed here are best determined by experiment. The polymer and fluids are sealed into glass ampoules and heated with slow rotation in a glass-fronted oven. Phase diagrams can be constructed by observing the behavior of the mixture in the ampoules at several temperatures covering a range of concentrations. Figure 5 shows part of such a diagram for poly(ethylene terephthalate) (PET) and methylene chloride. Most important is the melting point curve CDE which begins at the right-hand side of the diagram at the melting point of pure PET polymer at about  $260^{\circ}\text{C}$ . The shape of this curve shows substantial interaction between the polymer and solvent. Depression of the polymer melting point is sharp, and there is a peritectic point D at about 70% polymer, suggesting compound formation at a ratio of one molecule of methylene chloride to one repeat unit of polymer:  $(-\text{OCH}_2\text{CH}_2\text{OCOC}_6\text{H}_5\text{CO}-)$ . Note that even at as low as 20% solids, the melting point C is  $170^{\circ}\text{C}$ , which is more than  $100^{\circ}\text{C}$  above the boiling point of methylene chloride. Just above melting line CDE is an area, numbered 1, of one single homogeneous liquid phase. This is the preferred area of solutions useful for extruding ultramicrocellular foams.

In the region of polymer concentration between 20 and 50%, a second phenomenon occurs when ampoules containing those homogeneous solutions are

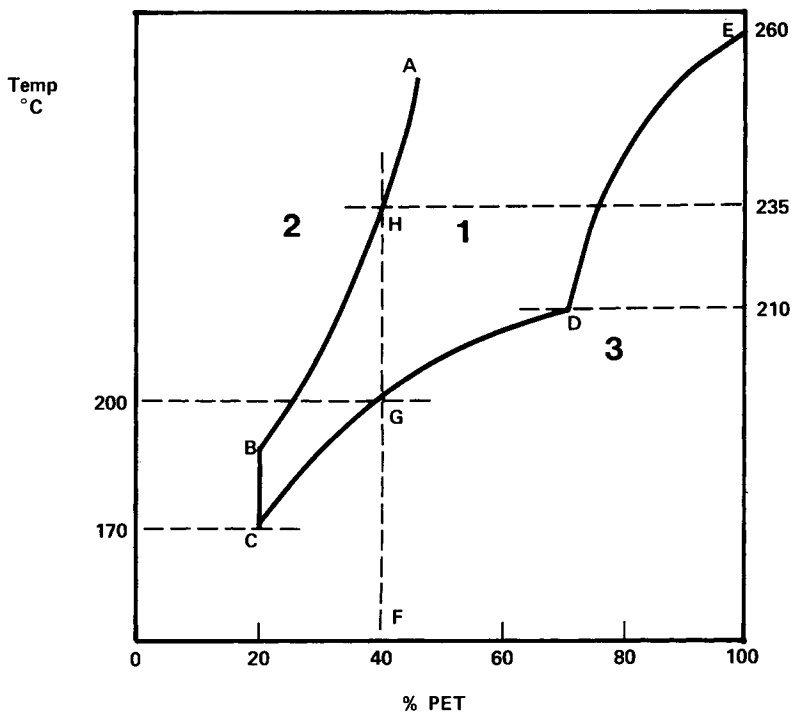


Fig. 5. Phase diagram for PET/CH<sub>2</sub>Cl<sub>2</sub>.

heated to higher temperature: the solution separates into two liquid phases. Curve AB connects these experimentally determined points and separates the area of one- and two-liquid phases. In area 2, the system consists of a mixture of polymer-rich solution and nearly pure solvent. Below 20% polymer, area 1 disappears; thus there is no region of stable polymer solution below this concentration.

Consider a typical ampoule experiment to make clear what happens in the area of most interest. Suppose a mixture of 40% PET and 60% methylene chloride is heated with the temperature increasing along the dashed line FGH on the diagram. At room temperature the polymer is neither soluble nor visibly swollen by the methylene chloride. As the temperature increases past 100°C, the methylene chloride is gradually absorbed by the slightly swelling granules of polymer, which become sticky. The methylene chloride disappears completely by 175°C. At the melting point G of 200°C, the swollen polymer lumps become clear, fuse together, and finally form a homogeneous solution which flows back and forth as the tube is slowly tipped end over end. As the temperature is further increased, little change is noticed until at 235°C (point H), the solution suddenly becomes hazy, and as the temperature continues to rise, more and more of the solvent-rich phase separates.

This chain of events is reversible. As the temperature is lowered back down from 235°C, the two phases mutually dissolve, and at the melting point the clear solution resolidifies if sufficient time is allowed. However, if homogeneous solutions in area 1 are cooled rapidly below their thermodynamic melting points into area 3, they are metastable for at least a few minutes. This delay in freezing allows foam extrusions to be made, in area 3, at temperatures low enough to

dissolve useful amounts of certain fluorocarbons in the polymer solutions, as described later on.

A typical spinning operation to make foamed fibers involves a solution of 50% PET/CH<sub>2</sub>Cl<sub>2</sub> at 220°C extruded at 1000 psi through a small circular orifice. At the moment of extrusion, the filaments are fully inflated with warm vapors of methylene chloride and have a density of about 0.02 g/cm<sup>3</sup>. However, most of the methylene chloride vapor permeates out quickly, and the remainder inside the cells, cools and condenses at room temperature, giving a collapsed, but still closed-cell, filament. These collapsed filaments have a density between 0.1 and 0.3 g/cm<sup>3</sup>, depending on how they are handled or collected after extrusion. The relative filament sizes—of the fully expanded foam before collapsing and then after collapsing—can be seen in Figure 6. Table IV shows some properties of as-spun filaments. The diameter on collapsing decreases to less than half, and the density increases tenfold. The tensile strength is about 0.6 dN/tex (~200 psi), and the elongation at break is about 50%.

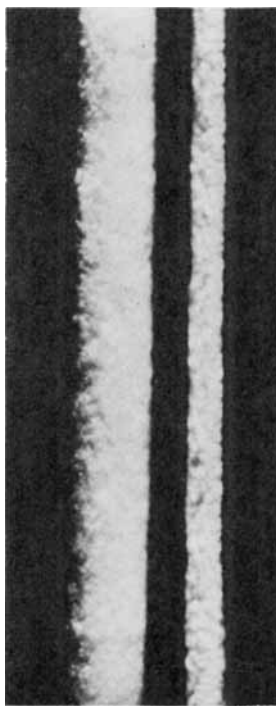


Fig. 6. Filaments of pneumacel.

TABLE IV  
Pneumacel Fiber Properties

Filament diameter	
As-spun	1.3 mm
Collapsed	0.50 mm
Density	
As-spun	0.02 g/cm <sup>3</sup>
Collapsed	0.20 g/cm <sup>3</sup>
Tenacity	0.6 dN/tex (~200 psi)
Elongation-at-break	45%



Inflation of the foam with fluorocarbon can be done in two ways: by dissolving the inflatant in the solution used for extrusion, that is, "spun-in" inflation, or by imbibing it in a later step, that is, a "postinflation."

The "spun-in inflation" process consists of dissolving the fluorocarbon in the solution before extrusion. If its solubility is high enough in the hot solution, enough fluorocarbon will be trapped inside the closed foam cells to provide the inflatant effects discussed before. In the case of polyethylene or polypropylene, certain fluorinated and chlorinated hydrocarbons can serve both as solvents and inflatants. However, in the case of poly(ethylene terephthalate) and nylon 66, a suitable inflatant has not been uncovered which is also a good enough solvent to serve both functions. Table V gives a specific example of a foam extrusion using a fluorocarbon additive to generate an inflatant-containing foam directly. A 50% solution of poly(ethylene terephthalate) in a mixture of dichloromethane and dichlorodifluoromethane is prepared by charging 400 g PET, 330 g methylene chloride, and 70 g Freon 12 to a 1-l. autoclave and heating, with stirring, to 210°C to dissolve. The temperature is then reduced to 190°C (into the metastable area of the phase diagram), and the solution is extruded at 800 psi from an orifice 0.05 cm in diameter, forming a filament about 0.25 cm in diameter. This filament is heated in air at 100°C for 15 min, during which time air replaces the methylene chloride in the cells. The inflated fiber then contains air at 1 atm. Table VI summarizes its physical properties. The cell walls are 0.1  $\mu\text{m}$  thick and have uniform texture and uniplanar orientation, and the remaining properties are similar to those discussed earlier. This "spun-in-inflation" method is in practice a difficult one to operate because it requires handling metastable solutions. In addition, it is not generally applicable because of the low solubility of highly fluorinated inflatants in hot solutions of polymer.

Where "spun-in-inflation" cannot be used, the "postinflation" process, i.e., a separate step after extrusion, can be carried out. This is done by treating the foam at or near room temperature with an agent which plasticizes the cell walls without causing them to lose their special and important molecular orientation. For poly(ethylene terephthalate), suitable agents are dichloromethane, trichloromethane, and sulfur dioxide. The plasticized foam is exposed to the desired inflatant until enough is imbibed, then the plasticizing agent is removed by

TABLE V  
"Spun-In Inflation" Procedure

Charge:	400 g PET, 330 g $\text{CH}_2\text{Cl}_2$ , and 70 g $\text{CF}_2\text{Cl}_2$
Temperature cycle:	210°C, 10 min; 190°C, 15 min
Pressure:	5500 kPa (800 psi)
Orifice diameter:	0.5 mm
After-treatment:	Heat 15 min at 100°C

TABLE VI  
Properties of Spun-In Inflated Pneumacel Fiber

Cell size:	20 $\mu\text{m}$
Wall thickness:	0.1 $\mu\text{m}$
Orientation:	110 and 100 reflections absent
Density:	0.023 $\text{g}/\text{cm}^3$
Tenacity:	0.5 $\text{dN}/\text{tex}^{-1}$
Elongation-at-break:	39%

rapidly heating the foam. Most of the inflatant is trapped inside the cells and remains there unless the foam is melted or plasticized again. This process allows great latitude in the selection of inflatant because the process is not so subject to the solubility/temperature constraints imposed by the extrusion process.

An example of an inflation procedure performed on a laboratory scale is given below. A solution of equal volumes of dichloromethane and 1,1,2-trichloro-1,2,2-trifluoroethane (Freon 113) is refluxed. A sample of deflated foam fibers having a density of about  $0.1 \text{ g/cm}^3$  is submerged in the refluxing liquid for 10 min, then withdrawn and immediately placed in a forced-draft air oven at  $100^\circ\text{C}$ . The foam inflates quickly as the liquids vaporize, the dichloromethane rapidly diffuses away, trapping the fluorocarbon inside the cells, and air diffuses in. After 10 min the inflated foam is withdrawn from the oven. It remains inflated in air at room temperature. After complete equilibration with air, the foam density is about  $0.015 \text{ g/cm}^3$ , one-seventh of its original density. The amount of Freon inside the cells can be measured either by weighing before and after inflation or by the change in weight on melt-pressing the foam to a film of solid polymer. This amount of Freon may be controlled by varying the time in the liquid inflation bath, the concentration of the fluorocarbon, or the external pressure upon the system. By running the equilibration step in an autoclave under autogenous pressure at temperatures up to  $125^\circ\text{C}$ , very large amounts of inflatant may be incorporated into the foam, even to the point that the mass of Freon exceeds the mass of the polymer. However, for cushioning applications, a partial pressure of less than 0.5 atm is adequate for good recovery from load.

Useful cushioning products can be formed by laying down the pneumacel fibers described above into uniform batts and then treating the batts with a dispersion of a thermoplastic polymer binder system. After the water from the dispersion is evaporated and the binder is melted, the batts are compressed using a calender, the binder-coated batts are then cooled and bonded batts of any desired thickness are formed.

## APPLICATIONS

Development work has shown that pneumacel fibers can be used in fabrics, in blends with conventional foams or fibers, and as loose filling material, but these pneumatic cellular fibers are most useful when bonded together with thermoplastic binder in the form of planar batts to make "firm" cushioning products. Two different types of pneumacel composite cushioning materials have been emphasized: batt weights of  $0.026$  and  $0.040 \text{ g/cm}^3$  ( $1.6$  and  $2.5 \text{ lb/ft}^3$ ,  $0.3$  and  $0.5$  in. thick) for carpet undercushions and a lower specific weight batt of  $0.014 \text{ g/cm}^3$  ( $0.9 \text{ lb/ft}^3$ ,  $1.0$  in. thick per layer) for mattress, furniture paddings, and automobile seat cushions.

First, consider the properties of pneumacel carpet cushion in more detail. In Figure 7 the load-compression curves of pneumacel are compared with those of other rug underlays—all-hair, urethane foam, and waffle rubber. A relatively firm cushion (curve 2) is made for the contract carpet market (e.g., hotels, offices, schools), while a softer cushion (curve 3) is used for the residential carpet market. Tests show that the actual walking pressure of a foot on a carpet is about 15 psi. The slope of the load-compression curve at 15 psi indicates the amount of re-

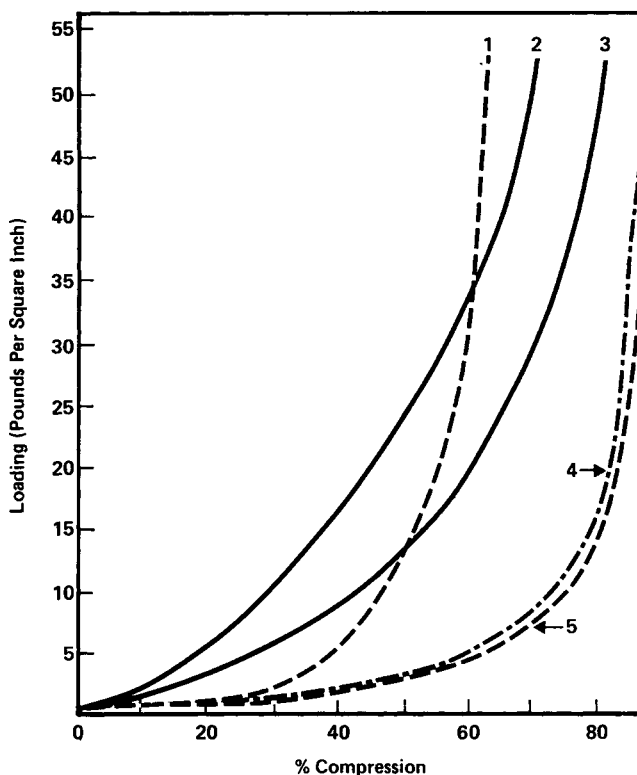


Fig. 7. Load-compression characteristics of typical classes of carpet cushion: 1, all-hair (40 oz/yd<sup>2</sup>, 0.30 in.); 2, pneumacel (9 oz/yd<sup>2</sup>, 0.30 in.); 3, pneumacel (9 oz/yd<sup>2</sup>, 0.48 in.); 4, waffle rubber (80 oz/yd<sup>2</sup>, 0.45 in.); and 5, polyurethane foam (23 oz/yd<sup>2</sup>, 0.45 in.).

sistance toward further downward movement. A hard, unyielding floor has a nearly horizontal slope indicating that a large increase in load causes little or no further indentation. Underlays having a flat slope at 15 psi have already bottomed out (1.8 psi for all-hair, 1.7 for waffle rubber, and 1.2 for densified polyurethane pads). In contrast, pads from pneumacel have a gentle slope (0.5–0.7 at 15 psi), which reflects their higher ability to deform and cushion under actual walking conditions.

An important requirement for a carpet underlayment is the ability to cushion the impact of a heel striking the carpet. Heel cushioning can be simulated by dropping a 20 kg mass (fitted with an accelerometer) onto a rug/cushion sample from a 1 m height. Lower peak accelerations correlate well with good walking comfort in subjective heel impact tests. The results in Table VII show that the two pneumacel underlays offer greater reduction of the shock of heel impact: this is because the pneumacel underlays compress the inflatable during deformation, build up the cushioning ability, and do not bottom out.

With regard to flammability, polyester pneumacel is not flameproof; it can be forced to burn with an open flame. However, largely because of its low density, it has a unique combination of low flame-spread, low fuel contribution, and low smoke and fume generation. Table VIII summarizes results from various burning tests. In the Steiner tunnel test, one commonly used by governmental regulatory agencies, pneumacel has a low flame spread rating (FSR) of under

TABLE VII  
Accelerometer Test Results

Sample	Peak acceleration, g
Pneumacel, 2.5 lb/ft <sup>3</sup> (9 oz/yd <sup>2</sup> )	1.75
Pneumacel, 1.6 lb/ft <sup>3</sup> (9 oz/yd <sup>2</sup> )	2.94
Polyurethane foam (23 oz/yd <sup>2</sup> )	3.94
All-hair (40 oz/yd <sup>2</sup> )	4.56
Waffle rubber (80 oz/yd <sup>2</sup> )	5.94
Solid floor	12.50

TABLE VIII  
Burning Characteristics of Pneumacel

Burns Poorly
ASTM E84 flame spread 0-20; fuel contribution $\approx 0$
ASTM 1692 and FAA vertical SE (= self-extinguishing)
ASTM E-162 flame index 23-41
Generates little smoke
ASTM E-84 smoke density 45-115
ASTM STP-422 $D_s$ max = 148 flaming, 83 smoldering
ASTM E-162 smoke 0.3-0.4
Emits low level of fumes
ASTM E-84 CO = 0.04%, CO <sub>2</sub> $\approx 0$ , SO <sub>2</sub> = 0

20 and a fuel contribution so low that standard instrumentation indicates zero. For comparison, the FSR scale is based on red oak at 100 and asbestos-cement board at 0.

Pneumacel also is a low smoke generator, developing a smoke density of only 105 or less, as measured in the Steiner tunnel test (ASTM E-84). To put this number in context, one prominent city fire-regulating agency accepts soft floor coverings provided the smoke rating in the Steiner test is less than 200. In the National Bureau of Standards smoke box, the smoke density maximum is 150 for flaming and 90 for the smoldering case.

Pneumacel carpet cushion is a low emitter of toxic fumes. As measured in the Steiner tunnel, it produces a rise in carbon monoxide level only 0.04% above the carbon monoxide being given off by the gas burner that heats the tunnel; the carbon dioxide rise is not measurable; and the sulfur dioxide output is zero. In the radiant panel test (ASTM E-162), the flame index ranges between 23 and 41, while the smoke index is 0.3 to 0.4.

Another key property of rug underlays is related to noise. Three acoustical properties are commonly used to characterize materials used in building construction and furnishing. The first is Impact Noise Rating (INR), which is directly related to cushioning ability and characterizes how well a floor covering or flooring will soften walking impact and prevent the generation of noise. Impact noise tests (Table IX) were carried out by Kodaras Laboratories on various combinations of floor, rug, and underlay. This higher-density pneumacel is a 0.3-in.-thick product, the lower-density material with the highest rating is 0.5-in.-thick.

The second acoustical property of interest in rug underlays is sound absorption by entrapment, as opposed to reflection; this is determined by measuring the change in the decay rate of sound in a reverberation room when the test specimen

TABLE IX  
Impact Noise Ratings<sup>a</sup>

Sample	Floor type	
	Concrete slab, 6 in.	Wood joist
Bare floor (control)	-17	-9
Carpet only	+14	+2
Carpet over 40-oz hair pad	+21	+8
Carpet over 44-oz waffle sponge rubber pad	+25	+14
Carpet over 9 oz/yd <sup>2</sup> , 2.5 lb/ft <sup>3</sup> , pneumacel	+25	+17
Carpet over 80-oz waffle	+29	+17
Carpet over 23-oz polyurethane foam	+34	Not available
Carpet over 9 oz/yd <sup>2</sup> , 1.6 lb/ft <sup>3</sup> , pneumacel	+35	+25

<sup>a</sup> Tests conducted by Kodaras Laboratories, Elmhurst, N.Y., in accordance with FHA 750; carpet used was 40-oz pile woven wool. Numbers are in decibels (db); 2 db is the significant difference level.

is brought into it. This indicates how well a floor covering suppresses echoes. ASTM 65-T averages the absorption at 250, 500, 1000, and 2000 Hz to give a noise-reduction coefficient. Table X compares the results for various underlays. The third acoustical property is sound transmission—which depends on energy absorption and tells how well a material prevents sound from being transmitted from one room to the other through a wall or floor. Pneumacel is not effective as a sound transmission barrier because it is both light and stiff, while an effective noise barrier must be massive and limp.

TABLE X  
Sound Absorption Data

Sample <sup>a</sup>	Noise reduction coefficient (NRC) by ASTM C423-65T
Pneumacel, 1.6 lb/ft <sup>3</sup> (9 oz/yd <sup>2</sup> ), 0.5 in. thick	0.65
All-hair (40 oz/yd <sup>2</sup> )	0.55
Pneumacel, 2.5 lb/ft <sup>3</sup> (9 oz/yd <sup>2</sup> ), 0.3 in. thick	0.50
Waffle rubber (80 oz/yd <sup>2</sup> )	0.50
Polyurethane foam (23 oz/yd <sup>2</sup> )	0.50
Carpet only	0.35

<sup>a</sup> All samples under tufted nylon contrast carpet.

TABLE XI  
Summary of Flammability Tests

Agency	Specification	Low-density pneumacel
N.Y. Port Authority	Radiant Panel, Flame Spread Index 100	60
Federal Aviation Agency	Vertical Flammability Burn Length 8 in. After Flame 15 sec Drip Flame 5 sec	6.1 in. 5 sec None
Dept. of Transportation	Horizontal Flame Spread 4 in./min	3 in./min

Pneumacel thus has a combination of properties which makes it useful as a rug underlay: subjectively desirable cushioning durability, impact and noise reduction, low flammability and low weight per unit area.

The second major area of application for pneumacel is as a lower-density batt for cushioning over springs (COS) in innerspring mattresses, automobile seats, and some kinds of upholstered furniture. These COS batts must mechanically insulate the feel of spring wires from the body and must conform to the shape of the body so as to be comfortable. Wire springs provide the lowest-cost form of resilient cushioning, but spring wires alone do not make a comfortable seat of mattress. They need some sort of padding to distribute the load. The spring "insulator" does the job, and it must do it without "boardiness": that is, it must do the insulating job without making the springs act in unison. Widely used pads for cushioning over springs are composites of sisal and cotton, or burlap reinforced with wires topped with cotton and some sort of an elastomeric foam. A pneumacel-insulated mattress construction is comfortable and firm without boardiness, allows no coil feel-through, and is breathable. Regarding durability, mattress manufacturers have developed an accelerated tester called the Juggernaut to predict mattress life. This tester consists of a 150 lb octagonal roller that is pulled back and forth across the mattress 250,000 times. In this Juggernaut test, pneumacel insulators maintain plumpness and cushioning because the cells tend to reinflate when a load is removed and any air squeezed out during the loading cycle diffuses back in. A mattress built with pneumacel padding is about 25 lbs (or 40%) lighter than its sisal/cotton counterpart, so it is a lot easier to turn.

One particularly useful property of pneumacel in spring-cushioning uses is its ability to be molded. Half-inch-thick batt material can be placed in light cane metal molds and expanded 2–2.5 times by blowing warm air through them.

The steps in this expansion molding process are as follows: first, a compressed sheet of pneumacel is placed between the male and female portions of the 20-gauge cane metal mole. Second, a draft of 140°C air is blown through for 20–30 sec, expanding the compressed pneumacel sheet to fill the contour of the mold. The shaped pad is then briefly cooled in the mold. After removal from the mold, the shaped pneumacel pad is placed directly over the spring unit.

The burning characteristics of pneumacel also make it desirable in this COS application. Table XI shows the results of several kinds of tests.

A market development facility located at the Christina site in Wilmington, Delaware was successfully operated for several years. In 1976 this unit was shut down and the further commercial development of pneumacel by du Pont was terminated.

## SUMMARY

Pneumacel fibers are made from closed-cell foams having thin cell walls, uniform distribution of polymer with high degree of molecular orientation; the fiber cells can find application in the form of bonded batts for cushioning: high-firmness batts as rug underlays and somewhat softer batts as cushioning over springs in mattresses and furniture. Pneumacel brings to these applications a combination of durability, firmness at low weight, and insulation from noise or heat.

**References**

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