FOAMED PLASTICS

■ Foamed plastics, sometimes called expanded, cellular or sponge plastics, are a group of low density (although some of the newer so-called "structural foams" are relatively high in density), high quality materials which can be engineered to meet specific end requirements of density, cell size, etc. Most thermoplastic or thermosetting resins can be expanded in volume to create such cellular structures (which resemble fine honeycombs or masses of tiny hollow spheres fused together).

Foaming can be accomplished by many processes, the most basic being 1) mechanical frothing, 2) dissolving a gas or a low-boiling-point liquid in the resin and 3) incorporating a foaming or blowing agent which will release an inert gas in the resin when the temperature is increased. Combinations or modifications of these methods are constantly being tried with a view toward obtaining still better materials more economically. The article on foaming agents, which begins on p. 370, provides an up-to-date look at some of the newer methods being used.

New developments

Progress, however, has been recorded not only with foaming agents but with the foams themselves. Based on the past year's activities, here is a brief rundown on some of the newer developments:

- Urethane foam, when impregnated with resins or other fluid reinforcing agents, can be used as a carrier in making RP panels or similar laminates. The flexible foam can be compressed so as to almost disappear between layers of a laminate. It can also be compressed tightly in some areas of the form and allowed to maintain its thickness to fill and reinforce ribs and other voids.
- A syntactic foam made of hollow glass spheres and epoxy resin is being used in deep submergence vehicle applications. The foam provides a buoyancy material in the 0.65 to 0.75 g./cm.^{3} density range capable of withstanding the 10,000 psi hydrostatic pressure required for such uses.
- Expansion molding of PE provides major economies in machinery and mold costs and gives a five-fold increase in production rate compared to injection molding. The foaming agent furnishes the pressure to fill the mold, yielding products with densities varying from 0.2 to 0.92 g./cm.^{3} Heels, soles, corks, carrying cases, etc., are among the diverse products now in production.
- Speed-up in urethane foam production lines is pointing the way to economies and larger-scale use of the foam. A refrigerator manufacturer has automated molded slab production. A construction firm applies a layer of foam to metal panels by a continuous spray process. Building panels consisting of urethane foam between flexible skin facings are made in continuous sandwiches and cut to desired sizes.
- A crosslinked acrylic foam features high thermal insulation value, ease of cutting and forming and a working temperature of 150° C. for a 0.0033 specific gravity material, higher than that for urethane or styrene foam. A prepolymer of acrylonitriles, acrylamide and acrylic acid is irradiated, placed in a mold and heated to expand it up to 40 times its original volume.
- Polypropylene cellular monofilament and solid film are beginning to compete with sisal as a raw material for baler and tying twines. A new polypropylene foam (Minicel-PPF, Haveg Industries) also has been introduced. A minute closed cell structure gives the foam rigid, non-friable and abrasion resistant characteristics. Various degrees of flexibility and resiliency can be introduced by adding selected modifiers without changing the cell structure. Foam sheets can be thermoformed.

On a more current basis, the following section treats with the chemistry, properties, methods of processing and applications of the leading families of cellular plastics. For a more direct comparison of the physical characteristics of the various foams, see the Foamed Plastics Chart, page 350.

urethane

BY C. E. LEYES, R. E. WEBER* and R. E. JONES**

■ The wide range of chemical and physical properties of urethane foams makes these strong, lightweight plastics suitable for a wide variety of applications.

Urethane foams are cellular plastics formed by an isocyanate and a polyol reacted in the presence of catalysts, cell control agents and blowing agents. By varying the ratio of raw materials or the foaming conditions, a broad spectrum of end properties may be produced. The foam may be formed inside a mold or cavity, sprayed on almost any surface or allowed to rise freely into a loaf-shaped mass. Almost as soon as the raw materials are blended together the foam begins to rise. Within minutes, volume increases from 30 to 70 times for low density foams and the cellular structure solidifies to permanent form.

The most important of the foams' properties that can be varied by adjusting raw materials are flexibility, resiliency and load bearing ability. The range extends from soft, flexible foams used in pillows to rigid foams used for load-bearing supports. Density ranges from one to about 70 lb./cu. foot. Characteristics of low density urethane foams may include buoyancy, thermal and acoustical insulation, shock and vibration absorption, durability and chemical resistance. As density increases many foam characteristics change. In addition, urethane foams can be tailored specifically to be self extinguishing, non-burning or to maximize other key properties.

Formulating foams

Polyols: Polyols are influential in determining the degree of flexibility or rigidity of a urethane foam. Moderately high molecular weight polyols with a relatively low degree of branching produce flexible foams. Their low crosslinking density permits an open cell structure and the molecular weight between each crosslink contributes to flexibility.

Lower molecular weight polyols with a high degree of branching produce rigid foams. High crosslinking density creates a closed cell structure and cells tend to be small.

The most widely used polyols are polyethers and hydroxyl terminated polyesters. For rigid foams, polyethers are preferred for producing desired properties at lower cost. Propylene oxide adducts of sorbitol, sucrose, diamines, pentaerythritol and methyl glucoside are among the polyethers used in rigid foams. Selection of the polyol depends upon viscosity, equivalent weight and hydroxyl number. Polyethers with hydroxyl numbers in the 350 to 600 range are used quite generally and polyols are frequently blended to obtain specific types of rigid foam properties.

The majority of flexible foams are also based on polyethers. Foams based on polyesters are used primarily in foam-backed and laminated fabrics and in packaging. Polyethers for flexible foams are based generally on condensates of polyhydric alcohols such as propylene glycol and glycerin. Ethylene oxide is frequently added to provide terminal primary hydroxyl groups for increased reactivity.

A recent development in rigid foams is the use of starch-based polyols. Low in cost, they are capable of producing foams with high functional properties and are being evaluated for various formulations.

Isocyanates: To form a polymeric structure, polyols are reacted with isocyanates. The hydroxyl groups of the polyol and the terminal NCO groups of the isocyanate react to build the polymer chain. In flexible foams, the most widely used isocyanate is distilled 80/20 toluene diisocyanate or TDI. In addition to TDI, other isocyanates, such as crude TDI and crude polymeric isocyanates, are used in rigid foams. Polymeric isocyanates give better self-extinguishing characteristics. They also have lower vapor pressure, making them easier to handle.

Blowing agents: Foams are generally blown in one of two ways: by the carbon dioxide generated when water reacts with isocyanate; or by using a volatile blowing agent such as fluorocarbon 11 or methylene chloride, which is vaporized by the exothermic heat of the polyol-isocyanate reaction.

In flexible foams, the load bearing ability of the foam can be controlled to some extent by the choice of blowing agents. In many cases a combination of water and volatile blowing agents is used. In rigid foams, fluorocarbon 11 is primarily used because of the low K factor it imparts to the finished foam. It also offers more attractive economics. The froth process uses both fluorocarbon 11 and fluorocarbon 12. Water-blown rigid foams are also available.

Surfactants: Cell formation is stabilized by the presence of surface active agents in the formulation. Silicones and organic surfactants, generally ionic, are used most widely to control the expanding gas bubbles. Surfactants serve to keep bubbles small and uniform, promoting uniform cell structure and higher rise.

Catalysts: Foaming reactions are accelerated by the presence of catalysts. Widely used catalysts are tertiary amines in combination with stannous or other metallic

(Continued on p. 352)

---

*Nopco Chemical Co., Plastics Div., North Arlington, N.J.

Foamed Plastics Chart

Type of material	POLYURETHANE FOAMS												CELLULOSE ACETATE	PHENOLICS			
	Open Cell (Flexible)	Closed cell (Flexible)	Foam-in-place (Flexible)	Closed cell (Rigid)							Closed cell (Semi-rigid)					
Forms available	Slabs Sheets Blocks Custom shapes	Slab Sheets Blocks Custom shapes	2 and 3 package system for mixing on job	Custom made shapes; standard size boards; One-shot, 2 and 3 package systems for foam-in-place; by spray or froth techniques								Boards and rods, (rigid, closed cell foam)	Liquid resin for foaming-in-place			
Standard sizes	Max width: 80 in.; max. length: 120 ft.; Thickness: $\frac{1}{16}$ - 30 in.	Max. width: 30 in.; max. length: 120 in.; Thickness: $\frac{1}{8}$ - 15 in.		Cut to size, or foamed continuously, or foamed-in-place							Foamed-in-place	Boards: 1 x 4 in., $\frac{1}{4}$ x 6 in.; $\frac{1}{2}$ x 8 in., any length Rods: 2$\frac{1}{4}$ in.; any length	–			
Density, lb. per cu. ft.	0.8-26.0	3-6	2-3	1.5-3	4-8	9-12	13-18	19-25	26-40	41-70	2.5-6	6-8	$\frac{1}{3}$ - 1$\frac{1}{2}$	2-5	7-10	10-22
Tensile strength, psi.	12-50	10-15	13-150	15-70	90-250	230-400	475-700	775-1300	1350-3000	3000-8000	20-50	170	3-17	20-54	80-130	–
Compression strength at 10% deflection	0.2-2 @ 25%	.2-1 @ 25%	0.3-4 @ 25%	15-50	70-275	290-550	650-1100	1200-2000	2100-5000	500-15000	–	125	2-15	10-35	158-300	300-1200
Impact strength, ft.-lb./in.	–	–	–	<0.05	–	–	0.32	–	0.45	0.45-1+	–	0.12	–	–	–	–
Maximum service temperature, °F. Dry: Wet:	260-275 212	260-275 212	260-275 212	200-250	325	325	325	325	325	325	260-275 212	350	Continuous service at 300			
Flammability by ASTM D1692-59T	Burnable, but self-extinguishing or non-burning when compounded	S.E.	Burnable, but self-extinguishing or non-burning when compounded									Burns slowly	Self-extinguishing			
Thermal conductivity, Btu/sq.ft./hr./°F./in.	0.23 @ 2 lb. per cu.ft. density	–	0.3 @ 2 lb. per cu.ft. density	Blown with fluorocarbon 0.11-0.17 Blown with CO_2 0.23	0.15-0.21 0.21-0.29	0.23-0.27 0.31-0.35	0.28-0.34 0.36-0.40	0.36-0.44 0.42-0.52	– –	– –	– –	0.31	0.21-0.28	0.20-0.22	0.24-0.28	–
Coefficient of linear expansion, 10^{-5} in./in./°F.	–	–	–	3-8	4	4	4	4	4	4	–	2.5	–	0.5	–	–
Dielectric constant	1.1	1.1	1.1	1.05	1.10	1.2	1.3	1.4	1.5	–	–	1.12	–	–	1.19-1.2	1.19-1.2
Dissipation factor @ 28°C.	–	–	–	–	0.0018	0.0032	0.0055	–	–	–	–	–	–	–	0.028-0.031	0.028-0.031
Loss tangent x 10^{-3}	0.5	–	0.5	0.3-1.3 @ 10^3 to 10^9 cycles			2	3	4	–	–	–	–	–	–	–
Water vapor transmission, in.	–	–	–	1-3	–	–	–	–	–	–	–	–	–	2 lb./ft.^{3} 2074 g 5 lb./ft.^{3} 1844 g per day m^2	–	–
Water absorption, % by volume	–	–	–	4 @ 2 lb./cu.ft.	1.8	0.8	0.4	0.2	–	–	–	13-17 @ 100% R.H. 1.9-2.5 @ 50% R.H.	–	13-51 @ 100% R.H. 1-4 @ 50% R.H.	10-15 @ 100% R.H. 1.5 @ 50% R.H.	

FOAMED PLASTICS CHART

Type of Material	UREA FORMAL-DEHYDE	POLYSTYRENE										STYRENE ACRYLO-NITRILE			SILICONES		POLYVINYL CHLORIDE			POLYETHYLENE		EPOXIES	
																	Plastisol with blowing agent	Open cell	Closed cell	Low density foam	High density foam	Spray-applied	Foam-in-place
Forms available	Block and shred	Products or shapes molded from expandable beads; finished boards				Extruded boards, planks and logs			Extruded film and sheet			Products or shapes molded from expandable beads; finished boards			Powder		Liquid or paste	Flat stock in sheets and rolls; cored cushions & other molded shapes; compounds	Sheets and molded shapes	Planks, rods, sheets, tubing and rounds	Molded parts and shapes with solid integral skin; density typically 35-40 lb./cu.ft.	2 package systems (liquid)	
Standard sizes	Block: $20\frac{1}{2}$ x $10\frac{1}{2}$ x $4\frac{1}{2}$ in.	Finished boards (tubed): 48 in. long; 18 and 24 in. wide; 1 through 4 in. thick, finished boards (loose): 18 to 144 in. long, 12 to 48 in. wide; 1 to 8 in. thick. Untrimmed blocks: 2 x 12 ft. x 18 in. and 4 x 12 ft. x 18 in.				Boards 12, 16, 24 in. wide; 1 to 4 in. thick; 8 or 9 ft. long. Planks 7 x 12 in. x 9 ft.; 10 x 20 in. x 9 ft.; 10 x 24 in. x 9 ft.			0.0005-0.125 in. thick up to 48 in. wide			Boards: 1 through 8 in. thick; 16, 24, 46 in. wide; up to 96 in. long. Billets: 16x24x96 in. 16x46x96 in.			Foamed in place @ 320° F. Cell size less than 0.08 in. Heat cure flexible		Foamed in place 3-30 lb./cu.ft. @ 310-400° F. closed or open cell, atmospheric or pressure molded.	$\frac{1}{16}$ to 5 in. thick 24 to 54 in. wide	$\frac{1}{16}$ to $2\frac{1}{2}$ in. thick 36 x 44 in. wide	Planks: $1\frac{1}{2}$ x 24 in. x 9 ft. max. Ovals: 2 x $5\frac{1}{2}$ in. x 9 ft. max. Rounds: 2x6 in. Rods: $\frac{1}{4}$ to 1 in. Sheets: $\frac{1}{4}$ x 48 in. x 125 ft. max. Tubing: I.D. $\frac{3}{8}$ to $1\frac{3}{8}$ in. x 9 ft.	–	–	
Density, lb./cu.ft.	0.8-1.2	1.25	1	2	5	1.8	2.5-2.8	3.3-4.3	6	8	10	0.5	0.8	1	14	32	10-2500	12 and up	4-25	1.9-2.6	35	1.8-2	2-2.3
Tensile strength, psi.	Poor	44-46	33-40	54-68	121-145	55-70	60-105	180-200	300-500	400-700	500-1,000	–	20	30	–	–	250-1200	10-200	–	20-30	1000	26-31	–
Compression strength, @ 10% deflection	5	12-20	14-18	29-35	95-115	16-32	30-80	120-130	42.5	52.5	68.0	1.5 @ 5%	6 @ 5%	8 @ 5%	200	325	–	–	–	5 @ 10%	800	13-17	20-26
Impact strength, ft.-lb./in.	Poor	–	.14	.21	.20	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Maximum service temperature, °F. Dry: Wet:	120	167-175				165-175			170-175	175	175	170-190			700		150	125-225		160	–	250	200
Flammability by ASTM✗ D1692-59T	–	All self-extinguishing when compounded										S.E. when compounded			Non flammable		S.E.	S.E.	S.E.	Slow burn	Slow burn	S.E.	–
Thermal conductivity, Btu/sq.ft./hr./°F./in.	0.18-0.21	0.245 @ 70°F. mean temp.	0.26	0.24 @ 70°F. mean temp.	0.25	<0.21-0.28 @ 40°F. mean temp.			0.24 (@ 70°F. mean temp.)			0.32	0.29	0.29	0.03	0.03	Depending on density	Depending on density	–	0.35-0.40	0.92	0.11-0.12	0.11-0.13
Coefficient of linear expansion, 10^{-5} in./in./°F.	–	1.8-7.4				3-4			–	–	–	–	–	–	–	–	–	–	–	9.5	4.18	–	–
Dielectric constant	–	1.05 @ 10^2 to 10^6 cycles				<1.05 @ 10^2 to 10^8 cps			1.27	–	1.28	–	–	–	–	–	–	–	–	–	–	–	–
Dissipation factor @ 28° C.	–	0.0001-0.0005 @ 10^2 to 10^6 cycles				<0.0004 @ 10^3 to 10^8 cps			0.00011	–	0.00015	–	–	–	–	–	–	–	–	–	–	–	–
Loss tangent x 10^{-3}	–	–				–			–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Water vapor transmission, g./hr./sq.ft./in./cm. of Hg	–	1.1-2				1-2			1.50	1.25	1.00	2-4			–	–	–	–	–	0.4	–	–	–
Water absorption, % by volume	–	Nil to less than 2				Nil			Nil			Nil			–	–	–	–	5 max.	1 max.	0.22	–	–

✗ Hor. Burn Test "Sample 2" x 6"
1½" Flame

salts. Careful control of foaming operations is required to obtain the desired properties and proper cure.

Additives: As requirements for specific performance properties grow more numerous and more demanding, additives for both rigid and flexible foam are becoming more important. Bromine, chlorine and phosphorus, which promote fire retardancy, are being used more extensively as urethane foams gain increasing acceptance in construction, aerospace and transportation applications. In flexible formulations, extenders are being added to produce higher density, weighted foams for seating applications. Forms of barites are favored as an extender. Other additives include dyes and colorants, nucleating agents such as talc and carbon black to control cell size, and special purpose additives to control hydrolysis or to overcome other handling difficulties during the foaming process.

Rigid foams

Rigid urethane foams offer outstanding performance advantages in thermal insulation, light weight, load-bearing strength, adhesion and buoyancy. Variations in formulation, in method and conditions of application and in foam density have a decided effect in determining performance properties.

In addition to high performance, ease of fabrication is an outstanding advantage of rigid urethane foams. Generally foamed at the user's plant or at the construction site, they may be molded into any shape, poured into any cavity as a filler and sealer or sprayed in place. Use of urethane foam frequently simplifies fabrication of finished articles, eliminating the need for many assembling and joining steps. Rigid foams also may be made into slab stock.

Manufacturing and fabrication

Most on-site foaming of rigid urethanes utilizes the semi-prepolymer technique. This technique involves two-component systems which include a resin blend and a prepolymer based on one of the available isocyanates. Reaction of the components takes place during the simultaneous blending and pouring of the two package parts. In some cases the prepolymer step is by-passed and crude isocyanates are reacted directly with the resin blend. This results in a reaction which is more difficult to control and which generates high amounts of exothermic heat.

One of the preferred methods of applying rigid foam is to pour it to fill curtain' wall sandwich panels, wall cavities and irregularly shaped voids. As the reactive liquid expands up to 30 times its original volume it fills the entire mold including crevices, corners and irregularly shaped spaces. Rigid urethane shapes may be cast in a mold in much the same way as metals, where the urethane hardens into a strong, seamless object. Release agents or films facilitate extraction of the foamed shape from the mold. Molds may be pre-heated to speed cure.

Many applications take advantage of the strong adhesion of urethane foams. Urethanes adhere tightly to metal, glass, wood, fibrous glass laminates, fabrics and most other surfaces. The pressure developed during foaming promotes strong adhesion, forcing the foam into the exact configuration of the cavity into which it has been poured. Molds or forms must be constructed to withstand the expansion and pressure created during foaming and the construction of the mold affects foaming and curing time and foam density. Molds constructed of metal or other materials which dissipate heat rapidly tend to increase the skin density of the foam and lengthen the curing time. Molds constructed of fibrous glass or other insulating materials reduce the foaming time. Because the heat of reaction is retained within the mold, the foam has more uniform density from surface to core. Similarly, the size and configuration of the mold affect foam density. Because of the efficient insulating properties of urethane foam itself, the heat of reaction in a large cross section is largely contained in the core of the foam. The result is a lowering of density. The ratio of surface area to volume also influences density. Higher densities are obtained by pouring into thin sections which maximize heat loss and restrict flow.

Frothing, a variation of the pouring method, is useful for narrow-walled cavities where high preheats are not possible. In frothing, fluorocarbon 11 and fluorocarbon 12, which are blowing agents of different boiling points, are mixed under pressure with the foaming ingredients. When the mixed ingredients are brought down to atmospheric pressure, the fluorocarbon 12, which is a low boiling material, expands instantaneously to form a froth, generally in the eight to 10 lb./cu. ft. density range. At this point the fluorocarbon 11 begins to vaporize as a result of the exothermic heat of reaction, and the foam further expands to its nominal two lb./cu. ft. density. Frothing does not necessarily result in lower pressure than properly formulated pour-in-place systems; foaming pressures are influenced by the rise-gel characteristics and extent of overfill of a system.

Spraying is an application method which is gaining wider use. Special spray guns which mix and atomize the components make it possible to spray thin layers of foam on ceilings, walls, tanks and other surfaces. The spraying technique utilizes the excellent adhesion properties of foam and eliminates the need for molds or supporting forms. Formulations with fast reaction rates are used to prevent sagging, and additional layers can be sprayed almost immediately. The rate of spray averages from four to eight pounds per minute.

Slab stock includes long flat sheets of rigid foam, cut into uniform thicknesses. Manufacture of slab stock starts with continuous buns of foam, generally produced and fabricated by a foam supplier. The buns are made by mixing and pouring components onto a conveyor line where the foam rises into a continuous bun as the conveyor moves. After about five minutes of rise, the foam is firm and ready for curing followed by trimming and cutting.

In all methods of application, heat is required to cure urethane foams. Usually the heat generated by the chemical reaction is sufficient to effect the cure and most foam systems do not require a post-cure at elevated temperatures. After curing, rigid foams have good solvent and chemical resistance and are non-toxic.

Finished rigid foams may be cut, sawed, stapled, nailed or painted by any of the methods used for wood. Urethane foams may be bonded to themselves or to other materials with standard adhesives.

Applications and properties

Refrigeration: Rigid urethane foams have spurred a revolutionary change in the design of all types of refrigeration and cooling equipment. Slim-wall home refrigerators and commercial drink dispensers, for example, make use of low density urethane's excellent low temperature insulation to boost storage capacity without increasing overall dimensions.

Rigid urethane foams made with fluorocarbons have the lowest thermal conductivity or K factor of any insulating material available. Ranging from a K factor of 0.11 to 0.16, rigid urethanes are approximately twice as efficient in thermal insulation as polystyrene foams and fibrous glass. The outstanding efficiency of urethane insulation reflects the low thermal conductivity of the fluorocarbons which are trapped in the closed cell structure of the foam. In a two lb./cu. ft. density foam, 97 percent of the volume is occupied by the gas and internal convection of conductive vapors is minimized. In addition to low K factor, the insulating efficiency of rigid foam is enhanced by being foamed in place. The foam rises to seal all crevices, eliminating points of potential heat loss. In refrigerated vehicles, for example, heat loss through crevices may be substantial when urethane foam insulation is not used.

Unlike insulating materials which are highly vulnerable to moisture absorption, rigid urethane foams are relatively unaffected by moisture. Other insulating materials lose efficiency as they age and grow heavier with moisture. The insulating efficiency of rigid urethanes is further enhanced by protecting the foam surface from air. Slab stock usually is sealed with a moisture vapor barrier. Foamed-in-place urethane seals itself by adhering to a structural wall or panel skin and thus has built-in protection against exposure. Properly formulated urethane foams provide insulation even at levels of cryogenic temperatures.

Efficient and light weight, urethane insulation has gained widespread acceptance for refrigerated transport equipment, soft-drink dispensers, food vending machines, commercial warehouses, storage tanks, pipe lines, home refrigerators and freezers and housewares.

Construction: Strength and insulating properties of urethane foams have opened many construction applications, which also take advantage of their ease of fabrication, either in pre-formed structural panels or on-site foaming. Current construction designs also make use of urethane's light weight and sound absorption properties.

Rigid urethane's combination of strength and light weight comes from its stable cellular structure. In a two lb./cu. ft. density rigid foam, only three percent of the total volume is composed of cell walls, with a compressive strength of 20 to 40 p.s.i. Low density urethane, foamed between light gage metal, plastic or [illegible] sheets, produces a lightweight panel with excellent support properties. The strength of urethane permits the use of lighter gage metals in wall panels. Corrugated metal skins add increased strength. Prefinished, lightweight wall panels are easy to install, cutting construction time significantly. A minimum of supports is required. Door and window openings and quick-locking joints are featured on many panels.

Less widely used than wall panels, urethane roofing slabs offer many advantages. Rigid foam is combined with a skin of specially surfaced asphalt felt. Panels 0.8 to 2.0 inches thick are adhered to the roofing bitumen with hot pitch or asphalt. The material has a high compressive strength and weighs 75 percent less than other panels with comparable insulating efficiency.

Structures may be made into unusual shapes with urethane foam, used either as a fill material or as a free-form support. Rigid urethane may be sprayed over low-cost forms, such as inflatable balloons, to build a structural shell. The rigid urethane shell is capable of supporting the dead weight of a sprayed concrete shell.

Flotation: Marine vessels, buoys, floats, docks and bridges use the outstanding buoyancy of rigid urethane foam. The hydrophobic closed cell structure keeps water out. One cubic foot of two lb./cu. ft. rigid urethane foam provides approximately 60 pounds of buoyancy. One of the best flotation materials available commercially, urethane foam is an ideal core material for thin-skinned structures. If a skin puncture occurs, the foam prevents the structure from sinking.

Unprotected foam has a low water-vapor permeability of one to four perm inches. Immersed in deep water for several days, foam will show only surface wetting. Submersion has little effect on the foam unless water pressure becomes strong enough to rupture the cell walls. Covered foam can withstand the pressures of extremely deep water. An interesting application is in salvage operations, where the foam system is pumped into voids of sunken vessels to displace the water and raise the vessel.

Recreational boats, surf boards and floats represent a growing market for low density rigid urethane foams. It also is being used extensively in life rafts and lifeboats.

Rigid urethane foam of 1.55 lb./cu. ft. density also has been used in keeping a Texas tower afloat during salvage.

Packaging: Rigid urethane foam is used in specialized packaging as a high-performance protective material. Light in weight and moisture resistant, it absorbs shock and vibration and eliminates recoil from sudden impact. In packaging objects of unusual shape, the objects are wrapped in a protective film to prevent adhesion and the foam is poured directly into the shipping container, rising up and surrounding the object completely. In another system, blocks of rigid urethane slab stock are placed between the object and the shipping container.

Potting and encapsulation: Rigid urethane foam makes a tamperproof assembly for protecting delicate electronic instruments against vibration, shock, corrosion, dampness and fungus. The foam's low density and dielectric constant of 1.06 to 1.60 provide excellent electrical insulation between adjacent components within the instrument. The foam may be poured or sprayed in place to hold components in a fixed position. The need for mounting brackets, clips and other bracing attachments is consequently drastically reduced.

Flexible foams

Flexible urethane foams offer outstanding advantages of resilience, load bearing and deflection strength, combined with light weight, high tear strength and effective insulation.

Such properties as flexibility, weight, density, texture, cell structure and compressive strength can be altered to meet the most varied specifications. Types of flexible foam can be produced to stretch up to 700 percent of their original length without breaking or tearing, to withstand dynamic pressures up to 150 psi, to resist temperatures up to 250° F., to stay flexible at —30° F. and to absorb up to 20 times their weight in water.

Polyether and polyester urethanes are available in flexible prefoamed sheets and slabs, supplied in the desired degree of density and flexibility, colored, molded to specifications, or cut to fit a contoured shape or pattern. Flexible urethane foams are easy to handle without tearing, because of high tensile and tear strength plus low density. Sheets and slabs are easily fabricated by sawing, slitting, die cutting, bonding with adhesives and heat sealing.

Flexible urethane foams also may be produced on-site by the same pour-in-place techniques used for rigid foams.

Applications and properties

Furniture: A combination of load bearing strength and resilience has made urethane foam a major material for upholstery and cushioning applications. Over 100 million pounds of urethane foam are used annually by the furniture industry. Compared to other types of foam, urethane is lighter in weight and has superior load deflection and aging properties. It also is easier to design and fabricate. New foams which give a feeling of weight and depth have been developed for luxury furniture. These foams are higher in density (2.25 to 5.0 lb./cu. ft.) than is generally available and sometimes are even weighted more with extenders.

Pre-cut cushion and upholstery shapes of urethane foam are favored by the furniture industry. Pre-cut shapes have helped to simplify construction and introduce important economies, eliminating the need for springs and fillers. Flexible urethanes also are used as a core material, wrapped with a batting of synthetic fibers. In another method of application, foam is laminated to upholstery fabrics.

Bedding: Approximately 50 million pounds of urethane foam are used annually by the bedding industry. Superior load bearing and load deflection properties make urethane foam an ideal bedding material. It is non-dusting and non-allergenic, unaffected by odors or mildew and flame retardant. Sterilized easily by autoclaving, urethane foam bedding is currently favored for hospital use; consumer applications are expected to develop for urethane foams in the near future.

Automotive: The largest potential market for flexible urethane foam is the automotive industry. Current models contain from three to four pounds of urethane; future models are expected to contain 7.5 to 10 pounds to enhance safety and comfort. Many automobiles currently have all-urethane seating, frequently molded into distinctive shapes. Most models use resilient foam for dashboard and visor padding as safety features. Flexible urethane foam also provides thermal insulation and sound absorption in trunk liners, headliners, rug padding and door panels. For many of these areas, the foam is laminated to vinyl sheeting, upholstery fabrics and carpeting. The laminates are easily installed as a single sheet of material.

Apparel: Over 200 million yards of urethane foam is used annually by the apparel industries. Flexible urethane, peeled to thicknesses ranging from under 1/16-inch to 7/8-inch is bonded by adhesives or by flame lamination to coat fabrics, dress fabrics and shoe linings. For coats and all types of outerwear, a layer of foam transforms light weight woolens, cottons and knits into a fabric with suitable body and durability. Insulating properties of the laminated fabrics are comparable to conventional fabrics weighing 100 percent more. Foam-backed fabrics are found in a large percentage of all-weather coats, children's snow suits, ski-wear and men's outer jackets.

An increasingly important use of foam is in fabric-to-fabric laminations. The thin layer of foam, serving as a bonding agent between the face fabric and the lining fabric, enhances dimensional stability. This technique, which greatly simplifies clothing construction, makes many delicate and light-weight fabrics suitable for a broadened range of applications and opens new possibilities for many types of coarse and textured fabrics.

In shoe linings, foam backed innersoles add cushioning and resilience. Lining fabrics also take on added visual depth and offer insulating advantages. Approximately 20 percent of all medium and low priced shoes now being made have some foam-backed linings.

Novelties: The cushioning and resilience of urethane foam are utilized in toys, sporting goods and household accessories. The capacity of flexible foams to absorb water (up to 50 lb./cu. ft.) makes them suitable for sponges, mops and wipers.

Packaging and protection: Ability to absorb sound, vibration and shock make flexible foams a favorite material for insulating sound chambers and electronic and radio equipment. Foam pads, slabs and sheets are used frequently in packaging fragile items and for the lining of shipping containers.

polystyrene foam

BY WILLIAM J. GORT*

As currently used by industry, styrene foam is available in two general forms . . . as an expandable molding or extrusion material, and as already-expanded boards or logs. The expandable material is molded into packaging components, insulated drinking cups, wig heads, ice chests, etc. It is extruded into film and sheet for meat trays, egg cartons, fruit trays and other packaging uses. The expanded foam finds wide use in packaging as well as in building and other insulation uses and in flotation applications.

Expandable polystyrene is produced as beads or pellets for molding or extruding into finished form. Film and sheet may be produced by extruding these beads or by extruding conventional polystyrene and feeding a propellant into the extruder barrel. Expanded foam, commonly referred to as Styrofoam or "bead board," is produced either by a novel extrusion process or by large-block molding of expandable beads. Since each of these foams involves quite different equipment and processing conditions, they will be discussed separately.

Molded styrene foam

The expandable polystyrene beads used to manufacture molded styrene foam products are produced by suspension polymerization where the propellant, a low boiling aliphatic hydrocarbon such as pentane or a mixture of pentane, isopentane and other fractions, is added to a stirred reactor containing water and polystyrene beads or pellets at elevated temperatures. A small quantity of suspending agent such as inorganic phosphate, polyvinyl alcohol or bentonite, and various anionic surface-active agents are used to stabilize the suspended beads (or pellets) and prevent agglomeration. Another method starts with styrene monomer and the propellant is added to the same reactor when the polymer beads are formed. A great number of patents cover areas of this field.

In recent years, the control of bead size distribution produced in the suspension process has been greatly improved. However, it is still necessary to screen the beads to eliminate fine beads and oversize agglomerates. In addition, the molding processes used and the products being manufactured (cups, blocks, etc.) have made it necessary to supply various screened sizes of beads. The introduction of internally colored beads has further complicated the bead sizing problem for the manufacturer as well as for the molder. Although the expandable polystyrene beads produced by various processes have different characteristics, they can generally be used interchangeably in a molding plant with some modification of molding conditions.

When the expandable polystyrene beads are exposed to heat, the vapor pressure of the propellant causes the beads to expand and form a myriad of non-interconnecting cells. The size of the cells is controlled by the type of propellant additives used during manufacture, the concentration of propellant and the age of the beads before expansion. The degree of expansion can be controlled by various methods to within the limits of two to 50 times the volume of the unexpanded particles (or within densities of 0.5 to 20 lb./cu. foot).

For the majority of applications colored or natural expandable polystyrene, Class 1 of ASTM D 2125-62T is used; but in cases where insurance or fire regulations require it, Class 2 or self-extinguishing expandable polystyrene is used.

Processing expandable polystyrene

The bulk of the expandable polystyrene is processed by molding in closed mold systems using various types of presses to hold the molds in closed position during the "fusion" cycle. The sequence is pre-expansion, aging or conditioning, filling the closed mold with the loose dry pre-expanded beads, introducing heat, cooling, opening the mold, ejecting the molded part (or removing it by hand) and drying. In some cases the dry parts are decorated or otherwise post treated for specific end uses.

The pre-expansion step is by far the most important in the process; unfortunately, it is the least understood and often the most poorly controlled. Not only do specific applications require definite densities to achieve the best properties, but control of density during pre-expansion has a major influence on subsequent molding conditions and ultimate manufacturing costs.

The most common methods of pre-expansion use either continuous or batch steam expanders, where the beads are exposed to saturated steam at different temperatures and pressures. In the continuous expander the beads are fed into an agitated drum at the bottom, using a Venturi feed system and steam and air mixtures to control the rate and temperature. As the beads expand they become lighter, rise in the expander, and finally overflow onto a screen where any agglomerates are removed or onto a conveyor belt where they are transported by air to storage bins for aging or conditioning. The temperature of the steam (or steam-air mixture) and the time the beads are exposed to the steam atmosphere (residence time) determine the density. In the continuous expander the residence time is dependent on the height of the expander, the type of expander, the agitation rate and the beads; the density of the pre-expanded product, therefore, is an average density.

The batch system of pre-expansion employs a rotating drum. A given weight of beads is charged into the expander and

---

*William J. Gort Associates, Consultants, 107 Goff Rd., Corning, N. Y. 14830 steam is introduced into the drum. The density is controlled by the time of exposure. Batch pre-expanded beads tend to fuse together and form small lumps so they are run through a grinder to put them in a form for molding. It is generally accepted that a batch pre-expander can produce lower density beads than the normal continuous pre-expander, but because of the low rates of output, this method has not been used to any great extent in the United States.

When the pre-expanded beads leave the expander, they are conveyed by air to well ventilated storage bins for "conditioning." The conditioning or aging time required varies with the density and type of beads; normally, the higher the density the shorter the aging time required. The conditioning process allows air to permeate into the cells of the pre-foamed beads until the internal pressure is equivalent to the external pressure.

Molding

Essentially, the foam molding process involves two distinct elements: the mold and the press. The application or end use normally determines the equipment to be used. For example in cup molding, the wall thickness and shape permit the use of thin machined molds of stainless steel with fully automatic, high speed presses; in block molding, size (thickness) is the most important since the blocks have to be cut to remove the skins; and in custom packaging the cost of molds is most important since the customer usually pays for the molds. The one uniform requirement is high units per hour at the lowest cost and, therefore, the mold becomes the most important part of the process and the press is required to perform the mechanical steps to accommodate the highest output-per-hour mold. This would indicate a requirement for either the largest press possible to accommodate a mold with the most cavities or the equivalent capital in single cavity mold presses. Since the most effective approach has not yet been established, a brief review of the various parts of the process should at least identify the areas which need improvement.

The molding process involves all or part of the following sequence: 1) Mold closes and drain is opened. 2) Pre-heat steam comes on during closing. 3) Press goes into stand-off position. 4) Moisture on mold face (from pre-steam) is blown off or steam is turned off to allow moisture to evaporate with heat. 5) Slide of slide runner mold is moved to fill position. 6) Fill air only for fill gun or fill air and boost delay for slide runner are turned on (boost comes on after delay). 7) Boost is turned off, fill air is turned off. 8) Press goes into clamp position (slide goes into up position). 9) Steam goes on (with or without drain closing delay). 10) Drain closes and pressure or time closes steam. 11) Cooling water delay and drain opens. 12) Cooling water on. 13) Cooling water off. 14) Delay and/or purge comes on. 15) Press clamp released, drain closes. 16) Air for chest pressurization to loosen part comes on simultaneously with clamp release. 17. Chest pressurization off, air eject manifold comes on (one side or other). 18. Press opens, part blow-off on. 19. Recycle delay. 20) Repeat cycle starts.

In many applications, specific operations are introduced in the electrical control system to control parts of the filling cycle, the fusion cycle, the cooling cycle and the ejection cycle. The object of all these controls is to obtain continuous automatic molding. In a cup molding operation, the sequence includes automatic inspection, counting, stacking and packaging and comes as close to a fully automatic system devised thus far. Just recently, a cup molding machine was tested where the pre-expansion of the beads is accomplished on the molding machine. Thus, for cups, a molding machine has been developed which literally feeds in unexpanded beads at one end and ends up with a completely packaged selling unit. Unfortunately, this same degree of automation has not yet been developed in custom molding, where it is vitally needed.

In the molding sequence outlined above, the press provides only the motion to open and close the mold; the control system provides the molding conditions required to fill, fuse, cool and eject the part from the mold. These four parts of the cycle are controlled by mold design and are covered in more detail below.

Filling: Filling a mold is a simple operation, but designing a mold to achieve near-perfect fill at all times can sometimes be impossible. Today, mold design is largely by trial and error, and the trials usually take place after the mold is made and put into production. The variables which make the mold filling operation such a problem include:

1) Cavity configuration. 2) Bead size and part wall thickness. 3) Air pressure and air/beads ratio in the stream (fill time). 4) Condensate from the last cycle. 5) Static charge on the beads. 6) Changing velocity of beads with density variation. 7) Changing pressures inside the mold caused by constantly changing venting. 8) Location of fill port. 9) Mold distortion during heating and cooling. 10) Venting variations due to machine wear.

When it is considered that most molds contain many steam entry holes (or core box vents) for fusion, these variables become a problem even for a computer to control. And as the number of cavities in a mold is increased, the effect of one change in a condition has an exponential effect on the filling characteristics.

Fusion: Assuming that a mold can be consistently filled properly, the fusion cycle then becomes the next most important part of mold design. Factors which control this are: 1) Raw material variation in molecular weight, density, age, residual volatiles and additives (lubricants). 2) Steam temperature and time. 3) Mold wall thickness. 4) Uniform steam distribution to avoid hot spots. 5) Temperature and moisture content of the pre-expanded beads. 6) Variations in initial venting. 7) Size of steam chest.

These variables are more easily identified and controlled and a pressure control system for steam time will compensate for many of them. The result of such compensation, of course, will be a longer cycle and lower output per hour.

Cooling: Because polystyrene foam is an excellent insulator, the largest portion of the cycle time of a particular mold is cooling. Cooling efficiency then depends on the rate of heat (BTU) removal, which depends on the amount of heat put into the mold and the beads. Theoretically, if the steam chest was insulated from the mold, and the mold could be made of thin walled aluminum or other rapid heat transfer material, the only BTU removal required would be the heat used to fuse the beads.

In current practice then, the variables which affect cooling are as follows: 1) Total heat input. 2) Thickness and density of part. 3) Mold wall thickness. 4) Steam chest size and weight. 5) Method of cooling (flooding, water spray or misting). 6) Dimensional tolerance of the part (allowable post expansion will permit shorter cycles).

Ejection: Even with optimum filling, fusion and cooling, *a molded part is not saleable until it is removed from the mold!* Additionally, the output of a mold can be greatly reduced if ejection becomes a problem. Ejection can be accomplished with air and/or mechanical knock-out pins or plates; for near-positive ejection every cycle, a combination of mechanical and air ejection may be used. However, as in filling, fusion and cooling, mold design is an important factor in good ejection.

The factors which generally affect ejection are: 1) Depth of part and draft allowed. 2) Location of air eject ports or knock-out pins (depends on part design). 3) Differential cooling. 4) Density of beads (finished part). 5) Release agents or Teflon coating on mold face. 6 Mold maintenance (depressed core box vents or large steam holes will cause hang-ups). 7) Variations in air, steam and water pressures and temperatures.

All too often, these variables and problems are not fully taken into consideration in part and mold design. As a result, disadvantages are built into the mold and the tedious job of finding and remedying the troubles is up to the molder. If the order is large enough, perhaps the problems can be solved before major losses occur. Because of these problems many molders minimize their troubles by using single cavity molding machines.

Other molding methods

There are other foam molding processes being used beside steam molding; however, they are either specific for a particular application or have yet to be developed to a point where they will obsolete the steam method. These methods include:

Autoclave: Certain articles are successfully molded by placing a filled, perforated mold into the steam chamber of an autoclave. This method permits cooling outside of the autoclave and, therefore, allows high production rates but with a high mold cost.

Steam probe: For many foaming-in-place applications, sandwich constructions and large area, thick-section applications, steam probes of various designs are used to introduce steam into the mold cavities.

Conduction heating: This method uses molds which do not provide for direct introduction of steam into the mold cavities. Heating of the material is accomplished by direct conduction through the mold cavity wall and the material itself. However, small amounts of steam are still required to obtain optimum product fusion and cycle. The primary purpose of this method is to permit the molding of skins on the outside of the foam part by exposing the surface to high temperatures. Both steam and other heating media (oil, etc.) have been employed in this area.

Radio frequency molding: The advantage of rapid uniform heating of beads with high frequency dielectric energy still represents a major potential process improvement. Since the minimum heat required is used, cooling times are materially reduced. The problem that must be solved is again the mold. Thus far, only plastic molds have been used and the methods of closing and opening these molds leave something to be desired.

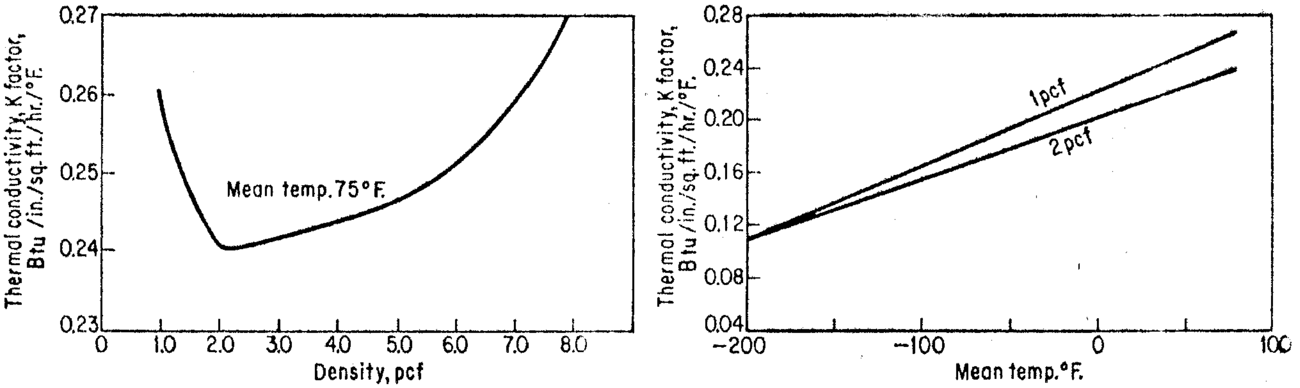
Screw injection: A new development in the molding of foams was introduced recently (see MODERN PLASTICS, July 1965) which uses a highly modified screw injection molding machine. Conventional plastic pellets are fed into the machine and an ammonium carbonate-based propellant is introduced into the extruder cylinder. The amount of propellant determines the density and the amount of material injected into the mold is automatically controlled. Because of a rapid temperature drop accompanying the expansion of the melt in the mold, the molded part ejected is fairly cool. Thus far, the new technique has been confined to polyethylene, but it is capable of molding any thermoplastic expandable resin at densities above 12 lb./cu. foot.

Foam sheet and film

Foamed polystyrene sheet and film are manufactured by a tubular film extrusion process using conventional methods with specially treated expandable polystyrene pellets, or by injecting a propellant directly into a section of the extruder barrel with standard polystyrene resins and additives. In both techniques, the extrudate passes through an annular tubing die and is expanded either by blowing air inside the tube or drawing the tube over an internal sizing mandrel. This enlargement of the tube (blowup ratio of 3:1 or greater) is necessary to eliminate the normal tendency of the foam to "corrugate" as it emerges from the die.

Because of the plasticizing effect of the propellant, relatively low extruder temperatures are required (220 to 260° F. profile). The type of screw and barrel length will depend on the process employed, the production rate and the thickness of the final product. Commercial grades of extruded foam are available in gages of five mils to 100 mils, 18 to 48 inches wide, and at densities from four to 20 lb./cu. foot.

Foamed film and sheet are commonly used to produce embossed



THERMAL CONDUCTIVITY of molded polystyrene foam varies with density at a given temperature, as at left above, and with temperature for a given density as at right above. (Diagrams, Sinclair-Koppers Co.)

packaging and decorative material, and for thermoforming, although polystyrene foam sheet is one of the most difficult sheet plastics to thermoform. It requires extremely uniform temperature control and indexing speeds and special mold design. Only a few tenths of a second can make the difference between correct forming temperature and overheating. The lower the basis weight (lb./msf) the more critical are the conditions. Basis weight or yield is a function of both density and gage.

Polystyrene foam sheet will generally expand when heated and the finished thermoformed part will have a greater cross-sectional thickness than the starting sheet material. If cross-sectional thickness is critical, matched metal molds must be employed.

Because of the compressibility of polystyrene foam sheet, trimming or die-cutting must be done with extremely sharp tools. Steel rule dies, precision-tooled steel punch dies and hot wire cutters have been used successfully in fabricating operations.

Expanded polystyrene foam*

Expanded polystyrene foam is produced by the free expansion to about 40 times its volume, through a slit orifice, of a hot mixture of polystyrene, a blowing agent and various additives. After expansion, the foam is cooled slowly to avoid undue stresses that might destroy the cell walls. After cooling, the material is cut to standard sizes, and the pieces are annealed to stabilize the cell structure.

Expanded polystyrene foam (e.g., Dow's Styrofoam) comes in densities ranging from 1.2 to six lb./cu. ft. and in a variety of sizes.

Expanded polystyrene can be fabricated with the usual woodworking tools, hand-operated or power-driven. It is essential that power-driven tools operate at high speed, and that the feed rate be low, in order to avoid tearing the foam. Tools must be kept sharp, and cutting blades should form an angle of about 110° with the surface of the foam piece to get a smooth cut and avoid tearing. It is recommended that polystyrene sawdust be continuously removed from the fabricating area to avoid trouble from eye and skin irritations.

Polystyrene foam parts can be bonded to [illegible] and to a great number [illegible] materials, but certain precautions must be observed in the selection of the adhesives used. *Drying type* adhesives (where the liquid—water or organic compound—evaporates) are useful since the porous structure of the foam allows the liquid to evaporate freely. For particularly tacky adhesives, joining of the sections is done after maximum tackiness has been obtained. *Setting type* adhesives (where full bonding depends on a chemical reaction, i.e., cement, plaster of Paris, or organic adhesives which polymerize) are also very satisfactory. Some must be mixed with a catalyst just before application. Among the *hot melt* adhesives, which must be applied at around 300° F., asphalt and wax-based materials are about the only ones used for the bonding of polystyrene foam. The use of adhesives which tend to attack the polystyrene (e.g., aromatic or chlorinated hydrocarbons) should be avoided.

Printing, decorating, coating

Foamed polystyrene can be printed by the flexographic or lithographic process for large volume runs, offset printing for multicolors, and silk screen printing for sharp print edges and fine details in multicolors. Low production rate and relatively high unit cost limit the use of the silk screen process to small volume runs. Roll leaf hot stamping wears well if the imprint is properly indented. Roller coating is used to decorate raised letters or designs.

Polystyrene foam can be colored with water- or alcohol-soluble dyes and pigments. Coatings are often applied to its surface for protection against damage by abrasion or weathering, or to produce a certain degree of flame retardancy.

Inks, paints, lacquers and other decorating or coating materials must adhere to the foamed polystyrene without attacking it to an undesirable extent. These materials achieve permanent adhesion through a carefully controlled solvent action which dissolves the foamed polystyrene slightly.

The solvent action must be adequate but must be limited, usually by proper evaporation rate and carefully controlled drying conditions. Change of drying conditions due to equipment

---

*The paragraphs on expanded polystyrene foam and on building-construction applications of polystyrene foam are based on information supplied by The Dow Chemical Co., Midland, Mich. 48640 variations or even a change of atmospheric humidity or temperature by exposure to drafts often seriously affects appearance and adhesion.

Properties and applications

Basically, polystyrene foam—whether produced from expandable beads or in the form of expanded boards or planks—offers very low thermal conductivity, good resistance to the transmission of water vapor and the absorption of moisture and resistance to relatively high static forces without deformation.

These attributes, coupled with good compressive, flexural and shear strengths, make styrene foam of special interest to the building industry. Both molded bead board and expanded polystyrene slab are involved, particularly as insulation board in such low temperature applications as cold storage areas, refrigerated display cases and coolers and low temperature piping. In addition, it can be used as a solid, insulated backup to gypsum, aluminum siding, ceramic tile, wood paneling and decorative wall board. In refrigerated transportation, it serves as insulation in various types of railway cars and truck trailers.

Building construction: In building construction, polystyrene foam board can be used as perimeter insulation and roof insulation. Low thermal conductivity and good structural strength also facilitate its use as a combination insulation and plaster base in residential masonry construction. Direct plastering over the foam is practical, since the surface requires no preparation.

In one construction technique, expanded polystyrene foam boards are used extensively in the construction of thin shell roofs. By contouring the foam boards to the forms and pouring a reinforced concrete roof directly over them, the foam becomes permanently bonded to the inside of the roof and serves both as thermal insulation and a base for the interior ceiling finish.

In another, known as "spiral generation," the expanded board is slightly bent and joined together by heat and/or with adhesives to create circular, domed structures for warehouses, tank covers, filter ponds, etc.

Finally, the high shear strength of polystyrene foam makes it an excellent core material for sandwich panel construction, especially where a lightweight insulating panel is required. Polystyrene foam sandwiches are also produced for use in walk-in refrigerators, cold storage room liners, and weather-resistant buildings.

Packaging: The next major outlet for polystyrene foam after construction is in packaging. Major areas in this field include the following:

Molded foam packaging components: Four properties—energy absorption (cushioning), light weight, insulation and ability to be molded to shape—have made polystyrene foam a major contender in the cushioning materials market. Probably the greatest advantage to the ultimate user is the opportunity for reduced packaging labor costs because of fewer package parts, more flexibility of use and less in-transit damage. Drum barbecues, lighting fixtures, servo motors, vacuum tubes, slot cars, steam irons, toasters and a host of other products are being packaged in foam primarily to reduce total packaging costs. More recently, interest has been generated for foam fruit and produce shipping and handling lugs. If the proper design and costs can be developed, this one application could consume almost 100 million pounds of expandable polystyrene per year.

The market for thin-walled insulated foam drinking cups has continued to grow and represents a major consumer of expandable polystyrene beads today. New interest in foam jars has developed with the advent of faster processes, colored beads and new coating materials. The opportunity to incorporate color, texture and skins in cosmetic jars of a variety of shapes has opened a new horizon for foam plastics.

Thermoformed packaging: Water resistance, light weight, and the insulating and cushioning properties of polystyrene foam, along with the availability of a variety of sheet materials, has stimulated the thermoforming of a wide variety of packaging items. Currently thermoformed meat and produce trays, bulk apple and egg trays, syringe packs and drug and pharmaceutical sample platforms are being produced commercially. Under investigation are egg cartons, laboratory glassware packaging and vending machine cups. Also being test marketed are take-out packages for hot dogs, hamburgers and pizzas where the thermal insulation of the foam sheet is an attractive advantage.

Sheet and film products: As the manufacturing process continues to be improved and raw material prices decline, sheet and film products, embossed, formed or laminated to paper, are making deeper penetrations into the paper products markets. A continuous thin sheet skived from a large molded cylinder of polystyrene foam and heat laminated to lightweight Kraft paper is being used to protect glass windshields and television bulbs during shipment. This same material is being tested for car headliners, door padding and sun visors.

Embossed or indented extruded foam sheet laminated to Kraft paper is currently under test as an inner liner for shipments of fresh fruit and produce to reduce or prevent bruising.

Packaging specialties: Two unusual forms of styrene foam have also found use in the packaging area. One is a loose fill (Pelaspan, by Dow) produced in spaghetti-like expandable polystyrene strands. When expanded, the strands form an extremely low density cushion packing medium which has a number of significant advantages in protective qualities, cleanliness, ease of handling and neat appearance over other materials now in use for loose-fill packaging.

More recently, pre-expanded styrene foam beads are being mixed with an adhesive and blown around a product after it has been encased in a PE film bag and set into a corrugated paperboard box. Thus, the beads can be made into an effective cocoon-like cushioning layer for packaged products—by-passing the molding steps and contributing to lower cost yet effective packaging.

Buoyancy: Polystyrene foam is used extensively in the field of buoyancy because of its light weight and closed-cell structure. With a buoyancy factor of 55 lb./cu. ft., it is used by boat manufacturers to replace airtight compartments, and by manufacturers of life rafts, aquaplanes, swimming rafts, navigation buoys and floating docks. It is also used in the construction of tankers and passenger ships

Other uses: In refrigeration and air conditioning appliances, polystyrene foam is used for drip trays, compartment separators and section insulation.

A wide variety of other miscellaneous products are molded from polystyrene foam. Examples of these are toys, novelties, displays, housewares and portable coolers.

The floral field finds expanded foam slab useful because of its light weight, attractiveness, colorability, and the fact that its cellular structure holds the stems of flowers firmly in place. The display and novely field uses polystyrene foam for holiday decorations as well as a variety of window and counter displays, carvings and signs.

foamed vinyls

*BY A. C. WERNER and A. D. VARENELLI**

■ Principal applications of foamed or cellular vinyl presently and in the recent past have been in the coated fabric and floor covering areas. Both the plastisol and calender techniques described below have been successfully used in coating natural and synthetic fabrics, paper and other type substrates with vinyl foam[1] having a non-foamed vinyl skin which provides an abrasion-resistant wear surface that may be further enhanced by lamination and printing for decorative effects.

In the coated fabric field such constructions have opened up large markets for vinyl foam-coated substrates for fabrication into winter jackets for the entire family; for upholstery material for furniture and automobiles; in ladies' accessories such as hats, handbags, shoes and belts, and in a host of other items where leather and conventional vinyl-coated substrates have been employed.

The principal advantages accruing from this laminate of vinyl foam between cloth and a vinyl wear surface are a suppleness and warmth not available in ordinary vinyl-coated cloth. These properties are provided by the softness and the thermal insulating quality of the foam layer.

A similar construction used in the flooring industry provides soft, warm, highly decorated and long-wearing products (e.g. Cushionflor by Congoleum-Nairn Co.). Here a vinyl foam is sandwiched between backing materials conventionally used in vinyl flooring and an abrasion-resistant wear surface to produce a laminate that has all of the desirable sales appeal of flooring that has been proved in service plus the cushioning effect of the vinyl foam.

Blowing agents

There are several techniques by which foamed vinyl may be produced. The principal ones used today use a high temperature blowing agent in the vinyl formulation such as azodicarbonamide (e.g. Celogen RAZ, Uniroyal-U. S. Rubber Co.).

Sufficient blowing agent (from two to five parts per hundred of resin) is employed to develop a foam density in the range of 10 to 20 lb./cu. foot. The softness or "hand" of the product is determined by both the foam density and the plasticizer level in the wear surface and the foam. Cloth coated products usually require 80 to 110 phr of plasticizer in the foam and skin. Jacket and clothing accessory stocks favor the higher levels, upholstery stocks favor the lower level.

Flooring products are based on lower plasticizer levels in both the foam and the wear surface. The activation temperature of azodicarbonamide is slightly above the fusion temperature of the plastisol system employed or the processing temperature required for calendered vinyl. This makes it possible to manipulate the product in its denser, unfoamed state before the blowing agent is activated.

Plastisol technique

A typical plastisol technique process for producing a cloth-foam laminate starts with the casting of the wear surface on a special release paper. This is generally applied at five to 10 mils by a knife or reverse roll coater and then oven fused. It is important that a minimum of fusion heat be employed so as to maximize the adhesion of the subsequently applied foam layer. After the skin coat is fused a foamable layer of plastisol is cast over it. This operation may be performed in tandem with the skin coating and fusion procedure by using a second coating and fusion unit, or during a second pass through the same unit.

The fabric backing then is applied in a number of ways. These include a lamination to the wet or partially gelled foam plastisol just after its application, or application of the backing to the foam after fusion either before or after foaming. In both of the latter procedures an adhesive coating is desirable. In any event, the construction must have a last pass through a high temperature oven to effect final fusion and foaming.

In calendering, a variety of fabricating techniques may also be used. The foam and skin layers may be produced separately on

---

*Senior Group Leader and Senior Research Specialist, Marvinol® Research and Development; Chemical Div., Uniroyal-U. S. Rubber, Naugatuck, Conn.

[1] For example, see U.S. Patent 2,964,799.

the calender, laminated together in a combiner with the cloth, and blown. In an alternate method the foam layer and cloth are brought together, foaming is effected, and the skin is laminated to the foam. This latter procedure provides a completely solid skin since no migration of bubbles from the foam into the skin can take place.

The technique selected for a production setup, i.e. casting or calendering, is for the most part dependent on the equipment available. However, industry experience has shown the calender process to be better adapted to the harder, lower plasticizer level stocks such as upholstery grades. On the other hand, the plastisol technique is suitable for a wider range of application; it is as practical for the very high plasticizer level formulations used in garment and clothing accessory stocks as for the low plasticizer compounds in foamed flooring.

These foam-cloth laminates are almost invariably embossed and color printed with vinyl inks, followed by a top coating of lacquer to develop a slip-type finish. Products of exceptional quality, hand and appearance result.

The technology of formulating plastisol and calender type compounds with high temperature type chemical blowing agent has been well developed. A variety of recommended PVC resins, plasticizers, stabilizer-activators, and other compounding ingredients are available to the formulator. One of the essential concepts in this development is that the compound must be in a plastic and cohesive state at the time the gas is evolved so that it can properly expand. Such factors as the particle size of the blowing agent and the type of activator-stabilizer selected influence the temperature and time of blowing agent decomposition, while resin molecular weight and plasticizer level and type influence the plasticity of the hot melt when the gas becomes available for expansion.

Pressure molded foam

Among the minor uses for vinyl foam is the manufacture of flotation equipment such as boat bumpers and life preservers, wrestling and boxing ring mats, padding for athletic equipment and a wide variety of shock absorbing and sound deadening applications. In this area, a molding method is used which is quite different from laminating procedures. The vinyl compound with blowing agent incorporated is placed in a mold and confined in a press under pressure up to 10,000 psi. The press is heated by steam or electricity to temperatures in the 350° F. range, which activates the blowing agent. Because the material is under pressure, gas evolved from the blowing agent is distributed throughout the plastic mass as tiny cells, each under pressure. After cooling, a post-expansion step is performed at 200° F. to complete the process. This again softens the plastic so that it can expand until the pressure in each cell is equalized and the pressure molded foam becomes stabilized and ready for its end use.

After post-expansion, an annealing period of several hours at 150° F. is recommended to avoid shrinkage of the foam in service. This method produces a foam with closed cells, i.e. not interconnected, and a low density of six lb./cu. foot.

Other plastisol techniques

Vinyl plastisol systems lend themselves to a variety of other foaming techniques, including mechanical foaming and variations of the chemical foaming procedures. Foam slabs can be produced on moving belt conveyors or cast into molds to make end products such as cushions through mechanical techniques like the Elastomer or Vanderbilt processes. In the Elastomer process, a gas under pressure is dissolved in the plasticizer portion of a vinyl plastisol, after which the system is allowed to expand rapidly at atmospheric pressure and is then fused with heat. This type of foam has rather large interconnected cells and a medium to low density.

In the Vanderbilt process, air is whipped into a specially formulated plastisol by means of a mechanical "foamer". Part of the formulation is a surfactant, which also contains a stabilizer. Foam prepared by this method has very small cells, also interconnected, and its density is somewhat higher than that of foam made by the Elastomer method.

Other chemical foaming methods at atmospheric pressure differ in the point of the cycle at which foaming actually occurs. For foaming at a relatively low temperature preceding gelation, a low-temperature blowing agent such as Nitrosan (Du Pont) is used. It decomposes at 190 to 220° F. For such a process the plastisol must be compounded so that its gelation is retarded until after the gas has been evolved. This allows for expansion of the plastisol while still in its fluid state. Gelation and fusion of the foam occur in rapid succession.

On the other hand, foaming may be made to occur simultaneously with fusion. Here, a blowing agent is used (viz. Celogen OT) which decomposes at temperatures within the fusion range of the plastisol.

Extruding foamed vinyls

Still another method of producing foamed vinyl is by extrusion. As a matter of fact, it has probably been so produced unintentionally from the first day that a vinyl compound was processed through an extruder. However, it was not then called foamed vinyl, expanded vinyl or cellular vinyl but, more often than not, that "blankety-blank" *porous* vinyl. And every effort was made *not* to produce it.

Today, foamed vinyls can be extruded under controlled conditions and with predictable properties. As a result they are being used in many products. In the wire and cable industry, cellular extrusions are of interest as cable fillers, cable jackets and insulation. In the building industry, cellular extrusions are used to make welting, weatherstripping, window spline and gasketing. Cellular vinyls also are being used for clothesline, as thermal insulation over flexible metallic tubing, and for profiles having a variety of end uses.

Foamed vinyl compounds for extrusion or injection molding are normally made by blending a chemical blowing agent into the base material. The choice of blowing agent will depend upon the composition of the vinyl and the processing techniques. Cellular vinyl compounds have been made by the use of azodicarbonamide, 4,4'-oxybis benzenesulfonyl hydrazide and other chemical blowing agents.

Vinyl extrusion compounds containing chemical blowing agents can be prepared in several ways, of which the following are most commonly used:

1) The simplest means of adding blowing agent to a vinyl compound, and perhaps the most economical in respect to inventory control, is to tumble the blowing agent with the granules. The blowing agent is held to the granules by static attraction and any simple tumbling equipment can be used satisfactorily. However best dispersion of the blowing agent throughout the matrix is not obtained with this method.

2) Blowing agents can be incorporated into dry blends simply by adding them to the blender during the blending cycle. The temperature of the blend must be kept well below the decomposition temperature of the blowing agent.

3) Intensive mixers, compounding extruders and mills can be used to prepare vinyl dice containing blowing agents. Again, to prevent premature activation of the blowing agent, the stock temperature must be maintained well below the activation temperature of the blowing agent during compounding. Good dispersion of the blowing agent throughout the matrix is obtained with this method.

The equipment used to extrude solid flexible vinyls can usually be used to extrude cellular vinyl. However, there are an infinite number of variables in the many vinyl formulations and in the processing equipment. These variables make it impossible to specify extrusion conditions for cellular vinyls, but the following generalized recommendations can be made:

Single flight screws with constant pitch, constantly increasing root diameter and low compression can be used to extrude vinyl dice containing a blowing agent. Screws with a higher compression ratio may be required for extruding dry blends.

The screw speed and design, in conjunction with the temperature profile, should be such that the temperature generated in the compound is high enough to completely activate the blowing agent. Regulation of the screw speed is also required to insure proper fluxing and blending.

The screen pack normally used for solid vinyls can be used for cellular vinyls and it can be varied to obtain the necessary pressures.

The temperature profile of the extruder will depend upon the usual factors such as screw and type of compound. Generally, the conditions required for the solid vinyls can be used.

Die temperatures

Die temperatures should be substantially lower than the stock temperature. By using a cold die the extrudate is cooled and toughened, thereby preventing tearing of the surface of the foamed extrudate.

Dies for the extrusion of cellular vinyl should have very short lands or no lands at all. Length of the die land becomes more critical as the hardness or density of the cellular vinyl decreases.

The die and guider pin should be positioned so that the pressure of the extrudate is as uniform as practical. An uneven flow can cause roughness on the extrudate.

Compound temperature should be high enough to activate the blowing agent. If the compound temperature is too low, a cellular structure will not be formed. On the other hand the compound temperature should not be too high. If the compound temperature is too high, the viscosity of the stock will be too low and the extrudate will not have sufficient hot strength to retain the gas.

Cooling equipment can be of the type normally used for cooling other plastic extrudates. The extruded cellular product expands immediately as it comes from the die and complete expansion occurs rather quickly. However, it is advisable to have the distance of the cooling medium from the head adjustable because the time of exposure of the extrudate to the air will depend upon its rate of travel.

The mechanical and physical properties of cellular vinyls, just as for solid vinyls, can be regulated by varying the resin/plasticizer ratio and by varying the other compounding ingredients. Also, the mechanical properties of cellular vinyls will vary with their density. Tensile strength and modulus decrease as density decreases. Elongation decreases as density decreases, but the rate of change is relatively small.

Injection molding

Cellular vinyl products may also be produced by injection molding on reciprocating screw injection machines. The greatest volume of cellular vinyl molding compounds used today goes into shoe soles.

Cellular vinyl moldings are of interest because they can be either soft and compressible or hard and inflexible. Molded cellular vinyls also have the inherent properties of solid vinyls—abrasion resistance, flame resistance, chemical resistance, water resistance and weather resistance, plus a warmness to the touch and a complete color range. Screw injection molded cellular vinyl parts have a continuous solid skin and a closed cell core.

The exact conditions required for molding cellular vinyls will depend on the size and geometry of the molded part as well as on the composition of the vinyl molding material. Optimum molding conditions can readily be determined with a little experimentation. The skin thickness, the density of the molded part, the cellular structure and the hardness of the molded part can be varied by compounding and processing changes.

The following general conditions are recommended for screw injection molding of cellular vinyls: 1) Compound temperature above decomposition temperature of blowing agent; 2) adequate venting of the mold; 3) fast screw speed; 4) rapid injection; 5) shot size just sufficient to fill a mold; 6) low injection pressures; 7) a warm mold; 8) sufficient dwell time in the mold.

polyethylene foams*

■ There are two distinct types of polyethylene foams available today: high density foam—20 to 30 lb./cu.ft. and above—or low density foam—around 2 lb./cu. foot. In addition, there are new techniques available today for extruding PE foam film or sheet and "expansion molding," described below under New Developments.

Low density PE foam

Low density polyethylene foam is made by mixing a foaming agent with hot, molten polymer under pressure, then releasing the pressure and cooling. Control of cooling time and, in certain cases, application of ionizing radiation, permits monitoring the cell structure of the foam.

Low density polyethylene foam has good cushioning ability over a wide range of temperatures. Like most foamed materials, it exhibits a certain amount of compressive set; that is, it does not completely regain its initial thickness after having been compressed for several hours. It resists the action of solvents and chemicals at temperatures below 130° F. Above that temperature, it softens in certain solvents. It is non-toxic, and although it has a burning rate of 2.5 in./min. (ASTM D1692-59T), chances are it will melt before it burns.

Low density polyethylene foam retains all of the commonly known properties of solid polyethylene (e.g., chemical resistance, moisture resistance, toughness and flexibility) and offers the added plus of weighing only about 1/30 as much as the solid material.

Polyethylene foam is used in many applications as a padding material. Because it has a buoyancy of 55 lb./cu.ft., PE foam is also being used as a positive flotation medium. Items such as boat bumpers, dock fenders, water ski belts, swimming aids, and floating toys are being produced.

Another interesting use for polyethylene foam is in the field of package cushioning. High-impact absorption plus the qualities of chemical inertness, moisture resistance, and nondusting appear to make the polyethylene foam ideal for packaging.

The automotive industry is using low density polyethylene foam in the form of gaskets for tail lights, heater housings, seals around the steering column where it extends through the firewall, and floor board seals. Compression resistance, closed-cell structure, and sufficient shape retention in thin slices to stay in place, enable polyethylene foam to qualify. In addition to sealing applications, it is used as a floor mat underlay.

Low density polyethylene foam's K-factor of 0.35 to 0.40 Btu/hr./ft.^{2}/°F./in. of thickness places it within the useful thermal insulation range. Polyethylene foam, because of its flexibility, is ideally suited for wrap-around insulation on large tanks and small copper tubing.

Buildings applications include: flexible insulated roof expansion joints, filler strips in the expansion joints of large structures, weather stripping and quality sealant backer rods in joints.

Fabrication: Low density polyethylene foam can be fabricated with standard power tools. Hot-wire cutting is also a practical method of fabrication.

Products of polyethylene foam can also be made by "thermal compression molding," and extruded sheets of polyethylene foam may be vacuum formed following conventional techniques with due regard to thermal and mechanical properties.

Sections of polyethylene foam may be joined together by bonding under heat. The heating tool used should be at a temperature of about 350° F. Generally the tool is coated with glass-reinforced fluorocarbon to prevent the foam from sticking to it.

Polyethylene foam can also be bonded to itself or to other materials with adhesives. Pressure-sensitive rubber emulsions and rubber-solvent contact adhesives are recommended.

Treatment of polyethylene foam surfaces prior to decorating or printing is necessary, either by flame or electronic treatment, or by chemical chlorination or oxidation. For certain applications, the polyethylene foam is coated with a synthetic elastomer, or with harder coatings such as polyester or epoxy.

High density PE foam

High density polyethylene foam (20 to 30 lb./cu. ft. or higher) can be made from either low density (0.915 to 0.925) or high density (0.941 to 0.965) polyethylene resin. At equivalent foam densities, foam produced from high density resin has greater tensile strength, better abrasion resistance, higher compressive strength, and is harder than that produced from low density resin.

High density polyethylene foam is a natural polyethylene which contains a great number of small isolated cells filled with inert gas. It is produced by heating an expandable compound until the resin softens and the blowing agent particles, dispersed throughout the resin, release tiny cells of gas at a great number of points within the mass.

Cellular polyethylene for use as wire and cable insulation is normally produced at densities of ⅓ to ½ that of the base resins; at this density it retains many properties of polyethylene—including chemical-, water-, and abrasion - resistance, flexibility, and toughness.

Cellular polyethylene finds use as primary insulation for communications cable (coaxial cables and television lead-in wire), because its good electrical characteristics, at all frequencies up to 10^{10} cycles, hold line losses and electrical attenuation to a minimum. The lower dielectric constant of cellular polyethylene permits the space between conductors to be reduced without

---

*Based on data supplied by J. S. Laing, The Dow Chemical Co., Midland, Mich., and H. J. Pazinski, Union Carbide Corp., Plastics Div., 270 Park Ave., New York, N. Y. 10017.

increasing the impedance characteristic. Consequently, 1) attenuation may be reduced and cable strength increased by increasing the size of the inner conductors without increasing the over-all diameter; or 2) weight may be reduced by decreasing the over-all diameter without decreasing the size of the inner conductors.

When immersed in water, the power factor of cellular polyethylene increases only slightly more than the power factor of solid polyethylene; dielectric constants do not increase significantly for either. When exposed to water vapor, the foam will pick up moisture and tend to reach an equilibrium with the immediate atmosphere. This will result in an increase in dissipation factor and high attenuation in cables. The moisture can be removed by drying in an oven. Drying will produce a decrease in dissipation factor and will bring attenuation back to normal. For maximum protection against moisture, a welded aluminum or copper jacket is required.

The combination of water-resistance, good insulating qualities, and buoyancy of cellular polyethylene insulation makes floating communications and signal cable possible.

In the 0.42 specific gravity range, cellular polyethylene has a thermal conductivity of about 0.8 Btu/in./hr./ft.^{2}/°F. Since this conductivity is high compared to commercial thermal insulations, it cannot compete in cost, unless its other properties provide special advantages. For example, the excellent chemical properties and low moisture transmission of cellular polyethylene suggest its use as an insulator for chemical laboratory refrigerators and cold boxes. Its relatively low melting point restricts its use to temperatures below 90° C. (194° F.).

Cellular polyethylene, in the form of extruded rod, disks sliced from rods, and disks stamped from sheeting, has also been used in such diverse applications as lightweight spacers, bumpers on small boats, floats, and cap liners.

Fabrication: Extrusion is the most commonly used method for forming cellular polyethylene. The long barreled, 24:1 L/D extruders with accurate temperature controllers and shallow channel metering-type polyethylene screws are recommended. This, along with good screw temperature control, will provide a uniform melt extrudate and result in uniform cellular composition. Subsequent uniform cooling of the extrudate will provide an optimum cellular construction. Best results are obtained by observing these general rules: 1) the time-temperature relations within the extruder must be adequate to decompose the blowing agent; an increase in through-put usually necessitates an increase in extruder temperatures for the same product; 2) pressures must be maintained uniformly high until the extrudate is released from the die; premature expansion of the cells must be prevented; 3) extrudate viscosity must be maintained at an optimum level (high extrudate viscosity produces higher density foam; low extrudate viscosity produces large, interconnected cells, surface roughness, and accompanying cooling problems).

New developments

A new continuous extrusion process for the production of closed-cell foamed polyethylene films and sheet has recently been announced.

Key to the development is the use of polyethylene pellets impregnated with a foaming agent in solution (details not yet revealed). After drying, the pellets can be extruded into film or sheet on blown film or flat die equipment. Pellets can also be blow molded directly into bottles or tubes (a blow molded thermal bottle is already commercial).

Like polystyrene foam film or sheet, the polyethylene foam can be thermoformed. It can also be heat-sealed, embossed, or laminated (with heat and pressure) to such substrates as cloth, paper, or urethane foam.

Originally developed as a decorative paper, the strength, toughness, water and chemical resistance, insulating characteristics and soft texture of the PE foam film now indicate other markets in such areas as: insulation for greenhouses or other structures; table cloths; foam film-to-cloth laminates for bags; embossed foam film-to-cloth laminates to compete with other synthetic leathers; insulation for electric wire and cable; tents; wallpaper; packaging; toys; outdoor signboards, and similar end uses where its specific properties and fabricating methods can be applied to advantage.

TABLE I: Typical properties of high density polyethylene structural foam*

Density (starting resin 0.96 density) g/cc	0.55
Tensile strength (parallel to skins) psi	1,000
Compressive strength (perpendicular to skins, 10% deformation) psi	800
Flexural strength (¼-in. thick sample) psi	1,900
Flexural modulus (¼-in. thick sample) psi	88,000
K factor, Btu/hr./sq. ft./°F./in.	0.92
Coefficient of thermal expansion, in./in./°F.	4.18×10^{-5}
Water absorption (24-hr. immersion, ¼-in. thick sample, unexposed edges) %	0.22

*Prepared by Plastics Div., Union Carbide.

Expansion molding: In a new foam molding technique developed in Europe, polyethylene pellets are fed from a hopper to a hot-plate-type turntable. The turntable makes six revolutions per minute and the pellets are evenly distributed on it in a thin layer. By the time they have traveled one complete turn they have been heated into a viscous melt that is scraped off the turntable by a doctor blade and directed into an extruder cylinder located above the table. Unlike conventional extrusion practice, entry of the material into the cylinder is through an opening in the bottom of the cylinder. Immediately upon entry into the cylinder, the material is picked up by the extruder screw (2½-in. diameter) and conveyed to the mold.

Ammonium carbonate-based propellant and any desired colorant are added directly to the extrusion cylinder and incorporated in the melt. The amount of propellant used determines the foam density.

The screw turns at a constant speed of 60 rpm. It requires about 1 hp. for each 10 kg. hourly output and conveys the melt to the exit nozzle and into the mold. Compression ratio is 3.5:1. While the melt is in the cylinder, pressure there is sufficiently high to prevent expansion. But as soon as the extrudate (generally in rod form) enters the mold, immediate expansion takes place and is complete within ¼ second.

The expansion of the melt is accompanied by a rapid temperature drop of about 40° C. (about 70° F.), so that the molded part is ejected fairly cool.

By proper selection of basic resin and control of feed and propellant, the finished product can have a broad range of densities and cell structure. Part finish is good, since the material picks up mold detail faithfully.

First commercial applications in the United States are in the shoe field, and involve heels and soles. Among other products for which this process appears to be suitable are automotive arm rests, suitcase handles, toilet seats, beer cases, window frames, toys, contour packaging, and stock shapes.

Structural foams: A new one-step method for foaming polyethylene and other thermoplastics and producing strong, tough, molded parts with integral solid skins has recently been developed. But details of the process will not be made available until patents have issued.

It is reported by the developer[1] of the process that parts molded of the new material, called "structural foam," are as much as three times as rigid as equivalent parts produced from the same weight of solid material. This means that equal rigidity can be obtained with one-third the amount of material, bringing new concepts of economy to the foam field. In addition, the process operates at low pressures and therefore can make use of inexpensive molds.

The characteristics of structural foam make it competitive with wood and metals in such applications as industrial tote boxes, agricultural field lugs, furniture drawers and in other areas to which it brings advantages of light weight combined with strength and rigidity.

It is reported that structural foam parts weighing 0.5 pounds or more and with minimum wall thicknesses of 3/16-inch are molded strain-free and with a complete absence of sink marks opposite ribs or bosses.

Polypropylene has also been foamed. There is only limited interest in the process so far, because of the brittleness of the foam at low temperature, but it is still being investigated. At equivalent foam densities, the polypropylenes will produce a harder, tougher, and more rigid product than polyethylene.

---

[1] Union Carbide Corp., Plastics Div.

phenolic foams

■ There are two basic types of phenolic foam—the reaction-type and the premixed cellular mortar or "syntactic foams."

Reaction-type foams

A rigid thermoset open-cell product, phenolic foams may vary from a rather friable, soft material of less than one lb./cu. ft. density to a hard, board-like foam weighing as much as 10 lb./cu. foot. Average strength properties of two densities of foam are listed in Table I. The color of phenolic foams is yellow to brown, and tends to darken with age. Basically, major characteristics of the reaction-type phenolic foam are light weight, high dimensional stability, heat resistance up to a temperature of 250° F. and non-support of combustion.

The foam is prepared by adding an acid to a water solution of phenolic resins and then incorporating a blowing agent and a surfactant. A number of acids may be used to start the reaction, including sulfuric, phosphoric, toluenesulfonic, hydrochloric, or phenolsulfonic. The heat of reaction causes vaporization of the small amounts of water and solvent present in the mixture. A proper balance of reaction and expansion results in the formation of a foam having a volume as much as 200 times greater than the original liquid resin.

The speed at which the foaming reaction will take place can be varied. The type of resin used and the relative proportions of the various components can also be varied to affect the nature of the phenolic foam obtained. For example, one part per hundred of mixture by weight of a wetting agent (e.g., Tween 40, by Atlas Chemical Co.) gives a uniform distribution of small cells. Reducing the proportion of wetting agent results in a coarse foam with large thick-walled cells; by substantially increasing the proportion of agent, a tough, resilient foam is produced. More water in the reaction also leads to the formation of large size cells.

Variations in blowing agent concentration must be great to produce significant changes in the foam, but changes in acid proportions result in setting of the foam before its full expansion, and hence higher densities.

In many cases, it is desirable to have a protective hard phenolic skin formed around a core of more friable rigid foam. By lowering

TABLE I: Average strength properties of phenolic foams*

	Density of foam, (lb./cu. ft.)	
	2	*4*
Compressive strength, psi	25	69
Flexural strength, psi	25	65
Shear strength, psi	14	30
Tensile strength, psi	20	42
Shear modulus, psi	400	750

*Data supplied by Union Carbide Corp.

the temperature of the mold in which foaming takes place, it is possible to form such a skin; the cooler the mold, the thicker the skin will be.

The low K-factor of reaction-type foams—0.20 to 0.22 for densities of one to three lb./cu. ft.—makes them desirable for thermal insulation, either in slab stock form or foamed-in-place. Huge cavities can be filled at relatively low cost, with only a small amount of crushing of the foam necessary to follow the surface irregularities. In building insulation applications, the reaction-type foam can be installed by: 1) filling wall spaces with precut, factory-produced slabs; or 2) foaming the material into horizontal prefabricated panels on a moving conveyor belt. Phenolic resin will foam in a vertical cavity to controlled heights.

Foam core panels, with plywood, Masonite, paper, or metal skins can be fabricated by laminating, bonding, or foaming in place. An adhesive is required when bonding phenolic foam to a smooth, hard surface such as found on glass or metals.

Phenolic foams, which are highly cross linked, are not much affected by heat or moisture, and retain their strength over a range of temperatures up to 250° F. They also retain their dimensions, with a minimum of shrinkage, up to a 16-hr. exposure at 350° F. Above 400° F., stability falls off.

On the other hand, phenolic foam, having an interconnected cell structure, transmits moisture and slowly absorbs water when immersed. The rate of absorption can be decreased by providing an outer, protective skin or a vapor barrier such as aluminum foil or polyethylene film.

The light weight, high dimensional stability, and non-support of combustion properties of phenolic foam make it an ideal form-fitting packaging material. The ability to produce a cavity of the desired size and dimension in phenolic foam by simply pressing an object, or a replica thereof, into the foam enables this material to be used advantageously in packaging applications.

In the case of consumer items where "dustiness" of low density foam would be objectionable, a coating should be applied to the foam after the cavity is press formed. This coating can be applied by spraying a conventional fast-drying paint or by vacuum forming a thin skin of rigid vinyl film over the entire foam block.

Reaction-type foam can be cut, carved, and shaped with conventional hand tools. The three lb./cu. ft. variety is particularly suitable as a handicraft material; it is easily worked with simple tools.

Syntactic foams

A different type of cellular phenolic, called syntactic foam, consists of microscopic hollow spheres of phenolic resin (Microballoons, by Standard Oil Co. of Ohio) mixed with a binding material such as a polyester or an epoxy resin. This produces a cellular mortar of low density and high strength. Diameter range of the spheres is from 0.0002 to 0.005 in. The average density of the mortar is 10 lb./cu. foot.

Normally handled as a putty-like mass, the cellular mortar can be troweled onto suitable surfaces (preferably with some form of heated trowel), molded to shape, or forced into cavities.

Cellular mortar is being used as a core material for such reinforced applications as boat hulls and decks, and reinforced sections of airplane structures.

Cellular mortar can also be used for simple do-it-yourself repairs on wood structures in homes or industry, for embedding electronic parts, for making heat shields and for prosthetic devices.

epoxy foams

■ Cured epoxy foams are characterized by high strength/weight ratio, chemical resistance, heat resistance up to 250° F. and adhesive qualities. Where the application requires, they can readily be foamed in place.

Their properties suggest use in such applications as "doppler" navigation systems for supersonic flights and various aircraft component checking fixtures, where absolute dimensional stability is needed. The epoxy foams also have been used for making involved tools and foundry patterns, spray-applied insulation over large areas—such as storage tanks—and in potting and encapsulating of electrical and electronic components.

Depending on the manufacturing technique used, epoxy foam density may vary between two and 20 lb./cu. ft., its compressive strength between 13 psi for the lighter density foam and 1100 psi for the heaviest variety. Tensile strength also varies greatly, again depending on density, from a low of 30 to a high of 500 psi.

Methods used for making epoxy foams include:

1) A heat-labile compound and a curing agent such as triethylene triamine are added to a liquid epoxy resin starting an exothermic reaction. Some water is added to increase the speed of the process; surfactants are also used to modify the surface tension. One drawback of this particular method is the uneven distribution of heat throughout the mass of the foam in formation, especially when large slabs or blocks are being molded.

2) An epoxy foam, using trimethoxy boroxine as blowing agent, has been developed. In production, the boroxine liberates methanol, with a polyamine, such as p'p' diaminodiphenyl sulfone, as catalyst. These foams cure without application of heat and remain rigid up to 300° F.

(More on foams on p. 369)

foamed silicones

■ Developed after World War II, silicone foams are produced from silicone resins and powders which are both organic and non-organic, containing the basic Si-O-Si siloxane group.

Room temperature foams are rigid or semi-rigid with densities of from three to five lb./cu. foot. They are prepared by mixing silicone resins with a catalyst, blowing agents, etc., and pouring in place within 60 seconds. Foam is ready to handle after ten hours. This time can be reduced, however, by heating the foam to 250° F. two hours after the expansion phase is completed.

These foams can be used at temperatures up to 650° F. They have excellent flame resistance, good electrical insulation properties, and a low order of water absorption. Their main applications are in the electrical field, and as thermal insulation where high temperatures will be encountered. Cell structure of this type of foam is small and uniform, and 60 percent of the cells are closed. Thermal conductivity is 0.281 Btu/in./°F./ft.^{2}/hr. Compressive strength is not very high; foam is nonburning and reasonably stable dimensionally up to 500° F.

RTV silicone rubber is a material that vulcanizes at room temperature to produce a low density (seven to 20 lb./cu. ft.) open cell structure which remains flexible and rubbery from −100 to +500° F.

This foam has very good electrical properties, it offers good resistance to weathering, corona, ozone, and moisture, and it is chemically inert. It is used essentially for vibration insulation and thermal insulation.

RTV silicone foam can be made flame-retardant by use of an additive masterbatch. One type of RTV foam is particularly adaptable to encapsulation by dip coating. It cures in 24 hr. at room temperature; at 150 or 300° F., cure time is accelerated.

Silicone foam sponge is obtained by mixing unvulcanized silicone rubber with a chemical blowing agent (such as N,N′-dinitrosopentamethylene - tetramine) and heating the mixture at vulcanizing temperature. Silicone rubber sponge finds use in the fabrication of blankets for heat sealing or bonding equipment, in electronics, and other insulation and/or cushioning applications involving exposure of the product to high temperatures.

One important new market for these foams is in the area of plastic surgery. Coarse cell silicone sponge appears to be useful for breast prosthesis, while the finer cell foam is preferred for facial implants.

cellular cellulose acetate

■ Produced by an extrusion process, cellular cellulose acetate[1] is known as Strux, or CCA. In production, molten cellulose acetate containing a volatile solvent is extruded and the solvent flash-vaporizes to leave a unicellular, white, rigid foam. CCA is furnished in the form of boards (1 by 4, ¾ by 6 and ½ by 8 inches) and rods 2¼ inches in diameter. Its density is from six to eight lb./cu. foot.

A dense skin forms during the extrusion of CCA and its removal is recommended for better bonding properties. This also reduces the as-extruded density by about 1 lb./cu. foot.

CCA has excellent strength properties, is thermally stable, and resists the attack of vermin and fungus. It has a broad temperature use range from −70 to 350° F. and will withstand temperatures as high as 380° F. for short periods. Mechanical properties are not greatly affected by temperature change. At −70° F., room temperature values are decreased about 20 percent.

Its K-factor is 0.31 Btu/in./°F./sq. ft. and it has a slow burning rate of 4.9 inches per minute. It has good buoyancy properties, absorbs little water upon immersion, and recovers full buoyancy when dried. Its good electrical properties—1.12 dielectric constant, 0.002 to 0.003 loss tangent—make it useful for X-ray and electronic equipment.

One of the most extensive current uses for cellular cellulose acetate is as a rib structure in the fabrication of lightweight, reinforced plastic parts made by matched metal and autoclave molding. Both small and large parts having skin thicknesses of between 0.020 and 0.032 of an inch are rigidized completely by the use of fabricated rib sections placed between the wet or pre-impregnated plies of glass cloth. The CCA withstands normal molding temperatures and pressures.

CCA also is widely used as a core material in sandwich constructions. In other fields it has found acceptance as reinforcement for aircraft control surfaces, radome housings and filler blocks under fuel cells. Inert to various fuels, it is used for many years in making tank floats for indicating devices.

Its buoyancy has led to its use in life floats, buoys and other marine flotation devices, as well as in small craft. Other applications include ribs, posts and framing in shelters and housing units.

For Literature References on Foamed Plastics, see p. 382.

---

[1] Manufactured by Strux Corp., 100 East Montauk Hwy., Lindenhurst, N. Y. 11757.

QUALITY BLOWING AGENTS
AT **LOW COST**
FOR PLASTICS AND RUBBER

- **Get better production control**
- **Broaden your market with expanded products**

CHOOSE YOUR PLASTIC—and there are 9 grades of KEMPORE® blowing agents each designed to get you a larger share of the growing foam market. Foam vinyls for flooring, insulation materials and luxurious coated fabrics used in garments, fashion accessories, luggage and upholstery covering. Foam polyolefins and obtain new functions like reduced slippage as well as low raw material cost. Let our technology help you achieve new production objectives and valuable new product functions.

CHOOSE YOUR RUBBER—and there's an OPEX® blowing agent to help you produce expanded shoe soles, mechanical goods, insulation, play balls — without discoloration or staining. OPEX disperses easily in elastomers, is dependably uniform, and will achieve excellent production results. Enjoy better production and improved products at lower cost.

Write for technical data and sample for evaluation.

NP® NATIONAL POLYCHEMICALS INC
54 EAMES ST., WILMINGTON, MASS. 01887 [617] 933-4240
Member of the Fisons International group
In Canada write: FISONS (CANADA) LIMITED, Toronto, Ontario

FOAM
MOLDERS

Looking for profitable molds? Millions of foam molded products are made daily in Springfield built molds. Our customers are located all over the world. Why do they come to Springfield? — Because we were pioneers and we are still the leaders in the production of high quality automatically operated molds. Our facilities provide for design, casting, machining and testing of E. P. molds. We make the best. Let us help you.

Write for brochure. Send prints for quotation.

SCP
MOLD DIVISION
SPRINGFIELD CAST PRODUCTS, INC.
616 Berkshire Avenue
Springfield, Massachusetts 01109

References

To locate additional information on Foamed Plastics and Foaming Agents in this Encyclopedia, consult the Subject Index, p. 6; for properties data, see the Foamed Plastics Chart, p. 350. For suppliers, see the Directory Index, beginning on p. 1118. For supplemental reading, see:

"Speeding up urethane foam production lines," Modern Plastics 43, 105 (Nov. 1965).

"Performance of glass spheres epoxy syntactic foam," by I. Resnick, Modern Plastics 43, 144 (Sept. 1965).

"New molding system," Modern Plastics 42, 92 (July 1965).

"Systems for foaming urethane refrigerator insulation," by C. K. Wolfert, Modern Plastics 42, 129 (Mar. 1965).

"A new look at plastics in building. Part 3—rigid foams," Modern Plastics 42. 108 Mar. 1965).

"How polystyrene foam expands," by S. J. Skinner, S. D Eagleton and P. J. Grey, Modern Plastics 42, 171(Jan. 1965).

"Chemistry and flame retardancy of rigid urethane foam," by E. A. Dickert and G. C. Toone, Modern Plastics 42, 197 (Jan. 1965).

"Foam molding in-plant to cut costs," Mod. Packaging 39, 148 (Sept. 1965).

"Formation of cellular plastics," by C. R. Thomas, Brit. Plastics 38, 552 (Sept. 1965).

"Economics of urethane foams—a summary," by M. A. Kohudic, SPE J. 21, 660 (July 1965).

"How to evaluate the rigid plastic foams," by H. Gerstin, Product Eng. 36, 59 (June 21, 1965).

"Novel process for molding urethane foam," by R. Moron and H. E. Schmetkamp, SPE L. 21, 470 (May 1965).

"Notes on the structure of polyurethane foams," by R. Merten, G. Braun, and D. Lauerer, Kunststoffe 55, 249 (Apr. 1965).

"One-shot semi-rigid foam system," by P. K. Heuster and D. P. Huntington, J. Cellular Plastics 1, 301 (Apr. 1965).

"Heat-resistant epoxy-boroxine foams," by H. H. Chen and A. C. Nixon, SPE Trans. 5, 90 (Apr. 1965).