

## Studies of Polymeric Systems for Absorbing Airborne Sound

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### Synopsis

Sound absorption properties of polymer systems were investigated as functions of temperature, frequency, and chemical composition. Viscoelastic polymers were mixed with rigid polymers to obtain improved acoustical performance. In the case of foamed polymers, it was found that the chemical nature of the polymer is the most important factor controlling sound attenuation if the thin membranes of the closed-cell foams are "acoustically transparent." Polyurethane-based polymer foams have been developed which possess excellent sound absorption characteristics. The foams are closed-cell, leathery, and "dead," and can absorb as much as 96% of the normal incident sound energy at 1250 Hz (foam thickness 25 mm). The temperature-dependent acoustical properties of various polymer systems are discussed in terms of viscoelastic theory of polymers.

### INTRODUCTION

Reduction of noise is desired to bring the level to a value which is not harmful and to reduce it further to an aesthetically acceptable intensity. The commonly used methods of solving such noise problems involve reduction of noise level at the source, changing the noise transmission path, or using a noise-attenuating device at the receiver.

The present methods of fabricating sound-absorbing materials include the production of polymer composites containing lead or other heavy powders or of a sandwich of polymer and lead foil. The lead will resonate, absorb some energy, and reflect the impinging sound waves in part back through the polymer where the acoustic energy will be absorbed by its energy-absorbing properties. One composite panel available is composed of an adhesive layer, a foamed polymer layer, lead foil, another foamed polymer layer, and finally a protective polymer film. This panel is about 2-in. thick and may be cut and fitted to the object being treated. There are coatings which may be painted or sprayed to a surface. Some are composed of polymers with sound-absorbing and damping properties, and it is these latter types which were further developed in this research.

Commercial polymer foams are usually open-cell and elastic. They have good sound absorption properties for air-borne sound at high frequencies, but the absorption at low and medium frequencies is poor. Also, the vibration damping efficiency (i.e., the ability to convert vibrational energy into heat which is dissi-

pated) is low. As the foams are open-cell, a protective film layer is used to keep them clean and protected. In order to increase the damping efficiency, a layer of viscoelastic material may be applied.

In this study, development of foamed polymers which would absorb air-borne sound and dampen structurally born sound was undertaken. Ease of application, low cost, and broad service temperature range were also desired. The idea was to enhance the viscous component relative to the elastic component of the polymer systems so that viscous dissipation of energy (i.e., as heat) is greatly increased, resulting in greater attenuation of the sound.

The ability of a material to absorb air-borne sound can be described in terms of the sound absorption coefficient  $\alpha$  and the specific acoustic impedance  $Z$ . The sound absorption coefficient is defined as the fraction of the energy of the incident sound waves absorbed by the material, and the specific acoustic impedance is the complex ratio of the effective acoustic pressure at the surface of the medium to the effective particle velocity.<sup>1</sup> The results are dependent on the frequency, temperature, and the nature of the polymer system.

If the material is a solid with a hard surface, the impinging sound waves will be mainly reflected. Most sound-absorbing materials are, therefore, porous in nature.<sup>2,3</sup> Poor sound-absorbing materials may be good sound insulators or sound barriers. A good sound-absorbing material may not be a good acoustic insulator if the material is porous and open-cell with interconnected, continuous air passages. Therefore, a porous sound-absorbing material is sealed at the surface with a thin, often perforated, layer.

The primary use of sound absorbents is to reduce the adverse effects of sound reflection by a hard surface inside an enclosure. The interreflection (reverberation) of sound will continue until the sound waves become weaker as a result of boundary friction at the walls. If the sound waves are continuously generated such as by an operating machine, the reverberation will build to a high sound pressure level if no sound-absorbing materials are present.

The mechanism of sound absorption by porous materials has been described.<sup>4-14</sup> When longitudinal sound waves impinge on the surface of a porous material, part of the acoustic energy is lost by reflection at the surface. The remainder penetrates into the material as an attenuated wave which sets the material and contiguous air in motion, dissipating the sound energy as heat.

For flexible porous materials and closed-cell foams, the mechanism is complicated and the theoretical treatment difficult. Experimental results<sup>4</sup> show that flexible open-cell foams give better sound absorption in the lower-frequency region, e.g., the absorption coefficient for glass fiber insulation at 300 Hz is about  $1\frac{1}{2}$  times that of a rigid structure. It is believed<sup>4</sup> that closed-cell foamed materials would have slight sound-absorbing properties, and they have been little investigated. If the closed-cell foams are flexible or viscoelastic, the above may not be valid, since such foams might convert acoustic energy into heat which may then be dissipated.

According to many studies,<sup>4-16</sup> sound absorption by a homogenous, isotropic, porous material is influenced by porosity ( $H$ ), specific flow resistance ( $R^*$ ),<sup>5,13</sup> structure factor ( $m$ ), the frequency of the applied sound, and the geometric factors such as thickness, length, and width. The acoustic impedance can be expressed in terms of these factors.<sup>5,18</sup> At low frequencies or for small pores, the acoustic disturbance will be attenuated by the walls resulting in isothermal

sound propagation. As the frequency increases, the gas tends toward an adiabatic behavior<sup>9</sup> resulting in additional sound attenuation.

However, two important factors which affect absorption of air-borne sound have been neglected—ambient temperature and the viscoelastic properties of the polymer matrix.

## EXPERIMENTAL

### Materials

**Hydroxyl-terminated polybutadiene (PB<sub>HTS</sub>)**, Phillips Petroleum Co., Butarez-HTS, viscosity 80 poises at 25°C.

**Copolymer of butadiene and acrylonitrile (NBR)**, 34% acrylonitrile Krynac 34-35, Polysar Ltd.

**Poly(ethylene oxide)**, Baker Chemical Co., average molecular weight 3000-3700.

**Polyester urethane foam**, Blachford Ltd., Aquaplas F.70.100 foam, a combination of a vibration damping layer over an open-cell polyester urethane sound-absorbing foam.

**Copolymer of styrene and butadiene (SBR)**, 80% butadiene and 20% styrene,  $\bar{M}_n = 2300$ , Richardson Co. Ricon1100.

**Poly(vinyl chloride) (PVC)**, Goodrich Chemical Geon 121.

**Poly(vinyl chloride)/butadiene-acrylonitrile copolymer blend (PVC-NBR)**, Goodrich Chemical Geon Latex 552, 50% solids suspension with an anionic emulsifier which after curing contains 50% PVC, 30% NBR, and 20% plasticizer.

**Poly(methyl methacrylate) (PMMA)**, Fisher Scientific Co.

**Polyurethane foam**, reticulated, Scott Paper Co., Coustex Acoustical Foam.

**Silicone surfactant**, Dow Corning foam stabilizer, DC-190.

**Triethylamine**, Eastman Chemical.

**Toluene-2,4-diisocyanate**, du Pont Hylene T.

**Caster Oil**, Fisher Scientific Co.

**Glycerol**, Fisher Scientific Co.

**Diethyl phthalate**, plasticizer for PVC, Eastman.

**Tricresyl phosphate**, plasticizer, Monsanto.

**2(2'-Hydroxyl-5'-methylphenyl)benzotriazole**, ultraviolet absorber, Ciba-Geigy Tinuvin P.

**Stannous octoate**, M & T Chemical Corp.

**Trichlorofluoroethane**, BDH.

**Lead powder**, 200 mesh, and **lead foil**, 1.6 mm thick, Fisher Scientific Co.

**Glass fibers**, chopped strands, 6 mm long, Fiberglas Canada Ltd.

**Lead alloy**, Canada Metal Co., Cerrolow-117, melting point 47°C, composed of 44.7% bismuth, 22.6% lead, 8.3% tin, 5.3% cadmium, and 19.1% indium.

**Barium sulfate**, BDH.

### Preparation

**Polyether Urethane Foam.** The foams were prepared using the following recipe (parts by weight): poly(ethylene oxide) 4000, 100; lead powder, 200 mesh,

2.0 (in making a base foam, no lead powder was used); Dow Corning silicone surfactant 190, 1.0; triethylamine, 0.2; water, 3.6.

To the well-mixed ingredients, 46.0 parts by weight of toluene-2,4-diisocyanate was added and the mixture stirred. Vigorous foaming occurred in about 10 sec. The foams were tack free after 25 min.

**Rigid Polyurethane-Based Foams.** The polyurethane-based foams were prepared using the following formulations (parts by weight):

Component A: castor oil, 100; glycerol, 28.6; stannous octoate, 0.286; D.C. silicone surfactant 190, 0.286.

Component B: tricresyl phosphate, 6.13; 2(2'-hydroxy-5'-methylphenyl)-benzotriazole, 0.214.

Component C: 10.7 parts by weight of *one* of the following modifiers: (1) poly(vinyl chloride)/butadiene-acrylonitrile copolymer (PVC-NBR) plasticized; (2) hydroxyl-terminated polybutadiene (PB<sub>H</sub>TS); (3) styrene-butadiene copolymer (SBR) (20/80); (4) plasticized poly(vinyl chloride); (5) poly(methyl methacrylate); (6) glass fiber; (7) lead powder, 200 mesh; (8) lead alloy; (9) barium sulfate.

Component D: toluene-2,4-diisocyanate, 85.7; trichlorofluoromethane, 34.3.

In each of the experiments, component A was blended for 2 min. The solution of component B was added and the mixture blended for 2 min followed by the addition of the modifier, component C. The mixture was blended for 3 min. Component D was added last and the mixture blended for 5 sec. The resulting mixture was immediately poured into a mold or container where it was allowed to foam (about 25–30 sec). The foam became tack-free after a few minutes. It was aged at room temperature for a period of 24 hr. The aging process could be accelerated by heating at 100°C for 10 min or at 60°C for 30 min. Some of the foams, for example, those containing poly(vinyl chloride)/butadiene-acrylonitrile copolymer (modifier 1), contracted after aging. To overcome this, it was necessary to concentrate the modifier from 51% solids to 71.4% solids and to increase the amounts of stannous octoate and Dow Corning 190 silicone surfactant (1.5 times the tabulated quantity). In another formulation, the same amount of SBR (modifier 3) was added to the mixture containing modifier 1 (71.4% solids) to give dimensional stability to the foams. These steps overcome what was probably a deleterious effect on the curing system of the water in the concentrated Geon latex.

### Test Procedures<sup>1,17,19–22</sup>

The acoustic absorptivity or the sound absorption coefficient is a measure of the ability of a material to absorb sound energy. It is defined as the fraction of the energy of the incident sound waves absorbed by the material. Thus, when a sound wave impinges on a material, the acoustic pressure and the reflected pressures at any point can be calculated or measured to give the total acoustic pressure. A microphone placed at various distances from the sample along the standing wave tube will receive an alternating acoustic pressure of measurable frequency and amplitude. Then, the absorption coefficient can be measured.<sup>19</sup>

The acoustic impedance  $Z$  is the complex ratio of the effective acoustic pressure at the surface of the medium to the effective particle velocity. Again using the standing wave tube, data can be obtained, the specific acoustic impedance can

be calculated,<sup>19</sup> and the phase angle can be determined.<sup>19</sup> Then the components of the specific normal acoustic impedance, specific normal acoustic resistance, and specific normal reactance can be read on the Smith chart.<sup>19</sup> The specific normal acoustic impedance can also be related to the normal absorption coefficient.<sup>22</sup>

The normal absorption coefficients and acoustic impedances of the materials were determined using a Bruel and Kjaer Standing Wave Apparatus Type 4002, according to ASTM Method C 384-58.<sup>23</sup> The apparatus has two measuring tubes; the larger one, with an interior diameter of about 10 cm, covers the frequency range from 90 to 1800 Hz, and the smaller one, with a diameter of about 3 cm, covers the frequency range from 800 to 6500 Hz. The standing wave apparatus was connected to an audio signal generator (Bruel and Kjaer Beat Frequency Oscillator Type 1014) and a measuring amplifier (Bruel and Kjaer Frequency Analyzer Type 2109). The normal absorption coefficient was read directly from the frequency analyzer at the first sound pressure minimum.

The effect of temperature on the absorption coefficient and acoustic impedance was also studied. This required a modified sample holder with a constant-temperature fluid circulating at the back. To minimize heat loss, the whole impedance tube was insulated. During the experiment, a continuous stream of dry oxygen-free nitrogen at the same temperature as that of the circulating fluid was passed into the tube to prevent condensation of water vapor from the air at low temperatures and oxidation of the polymer at high temperatures. Thirty minutes were allowed for the temperature to reach an equilibrium value.

The apparent densities of the materials were determined by the procedure described in ASTM Test Method D792-66 (Method A). The microscopic examination of the foams was carried out using a Nikon microscope with photomicrograph attachments. Specimen preparation followed the procedure described by Gegney, Batty, and Thomas.<sup>24</sup> A Cambridge Stereoscan (MK IIA) electron microscope was used to take electron micrographs of the foam specimen (with microscope stage tilted 45°). The glass transition temperatures ( $T_g$ ) of the materials were determined using a du Pont thermal analysis module with a differential scanning calorimeter (DSC) at a heating rate of 10°C/min, at atmospheric pressure, and under a nitrogen atmosphere.

### Experimental Errors

The measurement of normal absorption coefficients of the samples by the ASTM Test Method C384-58<sup>23</sup> was found to have an incremental precision of  $\pm 0.01$  over a range from 0.04 to 1.00. It is difficult to state the corresponding precision of impedance measurements in simple terms, but it varied between 0.05 and 0.2  $\rho c$  units, where  $\rho c$  is the acoustic impedance of air. The frequency calibration of the beat frequency oscillator was found to be accurate to  $\pm 2\%$  over the frequency range of 20 to 20,000 Hz. The temperature was measured by a thermocouple and was found to be accurate to  $\pm 1.5\%$  over the temperature range of  $-50^\circ\text{C}$  to  $180^\circ\text{C}$ .

The reproducibility of the samples (i.e., different batches of the same composition) depended on the technique of preparation. In general, when the samples were prepared under identical conditions, the confidence was 90–95%.

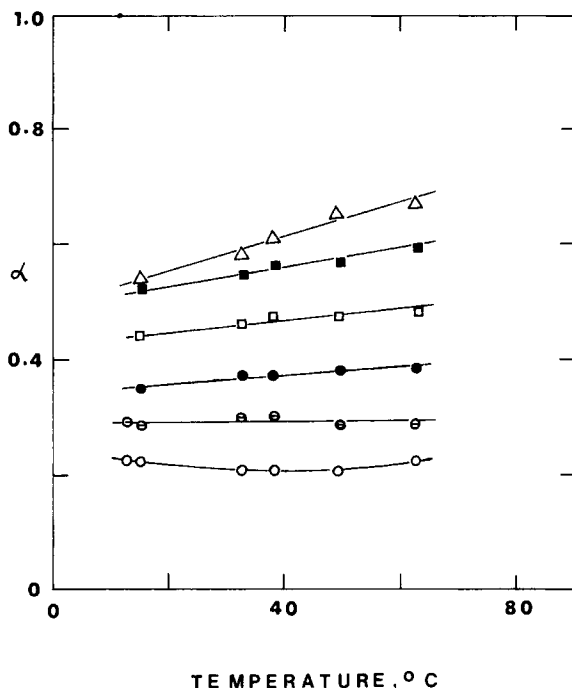


Fig. 1. Effect of temperature on sound absorption by polyether urethane foam at 1000 Hz (○), 1600 Hz (⊖), 3150 Hz (●), 4000 Hz (□), 5000 Hz (■), and 6300 Hz (△); sample thickness, 25 mm.

## RESULTS AND DISCUSSION

The sound absorption characteristics of foamed polymer systems are complex. Various theories<sup>1,4-13,15,16</sup> are used to explain the acoustical properties. They are based on the concept that the fibrous and open-cell absorbent material has a rigid skeleton. However, for many materials this is not the case. Among these are the flexible and closed-cell foams which will be discussed.

### Effect of Temperature on Acoustical Absorption of Elastic Polyurethane Foams

The effects of temperature on sound absorption of an elastic polyether urethane foam and the foam containing 2 parts of lead powder per 100 parts of the urethane are shown in Figures 1 and 2. The results indicate that temperature has little effect at low frequencies, but at high frequencies the absorption coefficient increases with increasing temperature and the relationship is linear. This behavior can be explained by Scott's theory<sup>4</sup> that gas behaves in an isothermal manner at low frequency when there is time for energy transfer and tends toward adiabatic behavior as the frequency increases. This results in little change in sound absorption at low frequencies. When the gas behaves adiabatically, work is done by the gas at the expense of its internal energy. The temperature changes create localized temperature gradients which promote a transfer of heat between alternating sound pressure regions by thermal conduction. This, in turn, contributes to a loss of the acoustic energy within the gas.

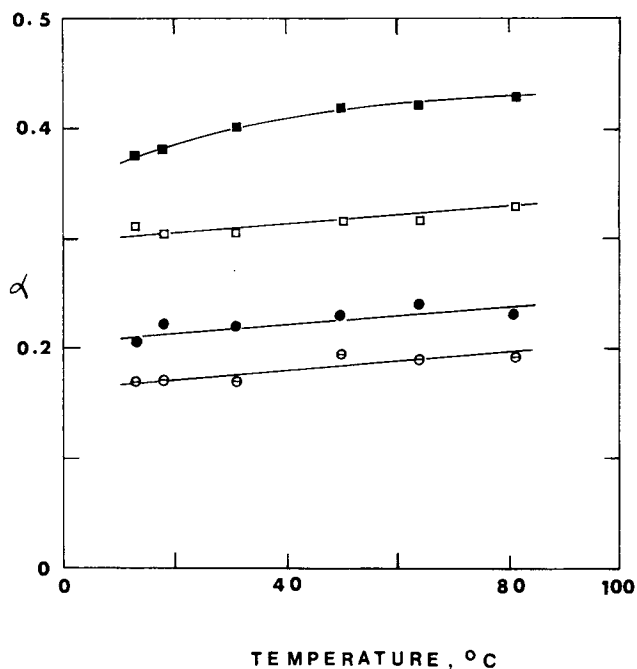


Fig. 2. Effect of temperature on sound absorption by polyether urethane foam filled with 2 phr lead powder at 1600 Hz (⊖), 3150 Hz (●), 4000 Hz (□), and 5000 Hz (■); sample thickness, 25 mm.

Much work has been done on open-cell foams in studies of noise pollution abatement, but the effect of temperature has not been extensively investigated. Temperature may be a major factor since in engine compartments, the temperature may reach 60°C. Figure 3 shows the normal sound absorption coefficient

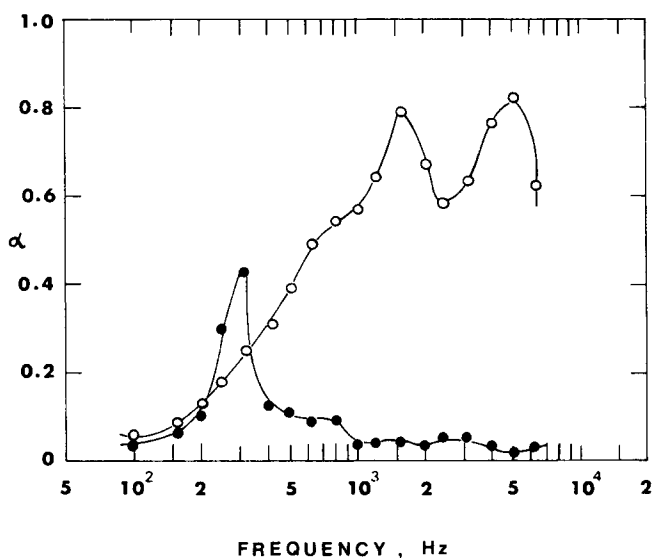


Fig. 3. Absorption of airborne sound by Aquaplas F.70.100 polyurethane foam (25-mm thick) at 60°C: (O) foam with Aquaplas F.70 backing; (●) foam with Aquaplas F.70 covering.

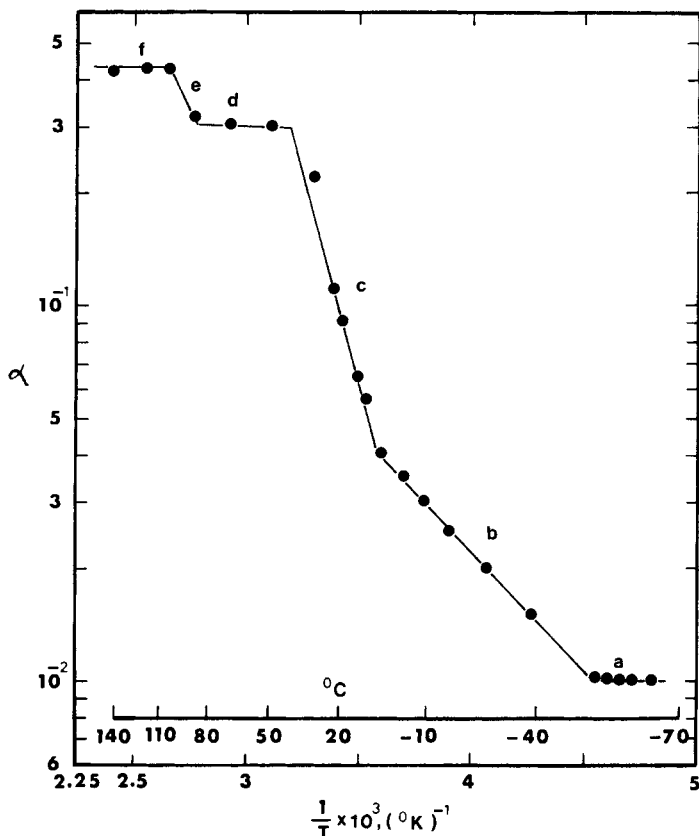


Fig. 4. Plot of  $\log_{10} \alpha$  vs.  $1/T$  for polyester urethane foam covered with a layer of viscoelastic material at 250 Hz; sample thickness, 25 mm.

of Aquaplas F.70.100 foam at  $60^\circ C$ . The foam is of the polyester urethane type, flexible, has a density of  $3.3 \times 10^{-2} \text{ g/cm}^3$ , and is covered with a 0.09-cm-thick layer of a highly viscoelastic material. When the foam side was facing the sound source, the material did not absorb much acoustic energy at low frequencies, but a considerable amount of acoustic energy was absorbed at high frequencies (1000–6300 Hz). There are two variables to be considered. One is the frictional air resistance inside the foam, and the other is the material making up the cell walls and the viscoelastic layer on the back. At low frequencies, the friction loss due to air resistance is only a relatively small portion of the total acoustic energy applied; but at high frequencies, the converse will be the case. Since the cell walls are flexible, their motion will result in a loss of acoustic energy within the solid and at the gas–solid boundary layers. The result shows that there is a minimum in the absorption coefficient at 2500 Hz. This may be due to the selective absorption properties of the viscoelastic material used as the backing.

When the foam backing was reversed, i.e., the viscoelastic material was facing the sound source, a completely different absorption spectrum was observed. The absorption peak was shifted to 315 Hz in the low-frequency region. Since the coating was thick, the sound waves with low frequencies were mainly attenuated at the surface and within the viscoelastic layer through the conversion of acoustic energy by the viscous mass into heat which was dissipated. At higher frequen-



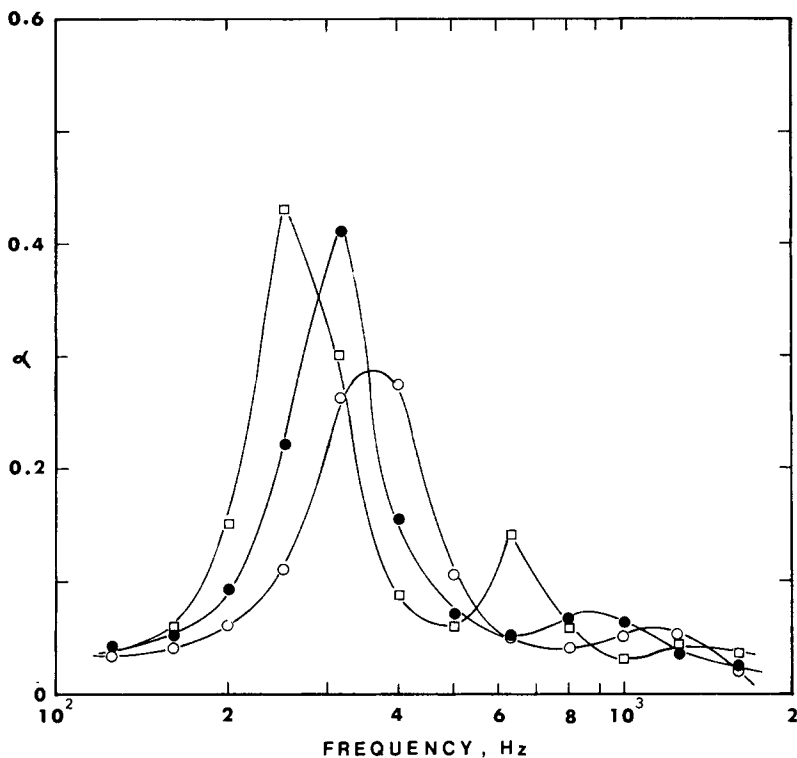


Fig. 5. Effect of temperature on the absorption peaks of polyester urethane foam coated with a layer of viscoelastic material (Aquaplas F.70.100 foam): (○) 13°C; (●) 30°C; (■) 102°C; sample thickness, 25 mm.

cies, the reactance of the material increased so that absorption was decreased. The decrease in the sound absorption coefficient at higher frequencies can also be due to the lack of surface openings.<sup>25</sup>

The acoustical absorption characteristics of the above foam at other temperatures are shown in Figure 4. At low temperatures, the absorption coefficient was low (below 0.05). It increased rapidly above 30°C until it started to level off at about 110°C. The mechanism involved is complex since the material is heterogeneous system consisting of a gas phase, a porous solid phase, and a nonporous viscoelastic phase. There will be complicated interphase reactions, but the absorption spectrum appeared to follow a definite pattern.

In an attempt made to explain the phenomenon six regions were identified: (a)  $< -52^{\circ}\text{C}$ , (b)  $-52^{\circ}\text{C}$  to  $5^{\circ}\text{C}$ , (c)  $5^{\circ}\text{C}$  to  $49^{\circ}\text{C}$ , (d)  $49^{\circ}\text{C}$  to  $88^{\circ}\text{C}$ , (e)  $88^{\circ}\text{C}$  to  $101^{\circ}\text{C}$ , and (f)  $> 101^{\circ}\text{C}$ . In the low-temperature region (a), the amount of acoustic energy being absorbed was negligible and constant. The material is glassy at such low temperatures so that the impinging sound waves are reflected. As the temperature is increased, more acoustic energy is absorbed by the material as indicated by regions (b) and (c). The transition from region (b) to region (c) is near the glass transition temperature of the viscoelastic material ( $T_g - 4^{\circ}\text{C}$ ). Since materials become highly viscous at their  $T_g$ ,<sup>26</sup> the rapid increase in sound absorption at temperatures near  $T_g$  is reasonable. Thus, the main factor which controls the attenuation of sound waves in region (b) and (c) is the viscous

component. The temperature coefficients for these two regions were found to be 2.93 kcal/mole and 10.38 kcal/mole, respectively. In region (d), the amount of acoustic energy being absorbed was again constant since the energy-absorbing capacity of the viscoelastic material at temperatures much above its glass transition temperature is considerably decreased.<sup>26-29</sup> In this region, the gas phase inside the foam must be the controlling factor in the absorption of sound energy. Then, at 88°C, the onset of region (e), the absorption coefficient started to increase, possibly due to another unidentified relaxation process in the polymer. The absorption coefficient again becomes constant in region (f) above 101°C, presumably the melt state.

Another important phenomenon, the shifting of absorption peaks arising from temperature changes should be considered. Figure 5 shows the effect of temperature on the acoustic absorption peaks of the polyester urethane foam. At 13°C, the maximal absorption occurred at about 370 Hz. As the temperature was raised to 30°C, the peak was shifted to about 250 Hz. The shifting of the absorption peak to lower frequencies at higher temperatures was also accompanied by an increase of the peak to a higher value. This shows that temperature is a controlling factor in attenuating the impinging sound waves whenever a viscoelastic material is added to a porous system.

#### **Effect of Chemical Composition on Acoustical Absorption of Polyurethane-Based Foams**

The performances of the foamed polymers and of two commercial foams are listed in Table I. The unmodified polyurethane foam (no. 1) had a rigid structure, and its absorption coefficient increased with increasing frequency, a result which would be predicted by theories.<sup>1,4-13</sup> Since the foam had a closed-cell structure with rigid cell walls, the impinging sound waves could not penetrate very far into the foam, and so the absorption coefficient was low, e.g., maximal absorption was only 49% at 5000 Hz. However, when rubbery or elastic materials such as hydroxyl-terminated polybutadiene (PB<sub>HTS</sub>), styrene-butadiene copolymer (SBR), and poly(vinyl chloride)/butadiene-acrylonitrile copolymer polyblend (PVC-NBR) were dispersed in the rigid polyurethane foam, the absorptive power of the foams was increased greatly, especially at low and medium frequency ranges. For example, the maximal acoustic absorption of 80%, 96%, and 87% occurred at 1250 Hz, 1250 Hz, and 2000 Hz, respectively, for the polyurethane modified by PB<sub>HTS</sub>, PVC-NBR, and SBR.

By the inclusion of the modifiers, the products were leathery and "dead" and would dissipate a greater amount of acoustic energy by an energy conversion process which may be represented by the following sequence: sound energy, elastomeric kinetic energy (resonant), viscous energy (flow) at interface and internal friction of viscous phase, and heat. The foams can also be considered as a two-phase system consisting of an elastic dispersed phase (i.e., air) and a viscous continuous phase (i.e. the interpenetrating polymer network). The sound pressure will set the elastic molecules vibrating in the viscous continuous phase resulting in frictional energy loss (i.e., viscous energy flow) at the interface. Therefore, the efficiency of energy conversion may depend on the interface surface area and the nature of the continuous phase. The interfacial surface areas of foams depend on the density and porosity of the foams. If the latter

TABLE I  
Absorption of Airborne Sound by Foamed Polymers at 60°C

No.	Polymer system Composition	Density, g/cm <sup>3</sup>	Absorption coefficient $\alpha$											
			125 Hz	250 Hz	500 Hz	800 Hz	1000 Hz	1250 Hz	1600 Hz	2000 Hz	2500 Hz	3150 Hz	4000 Hz	5000 Hz
1	Polyurethane (PU)	.057	.05	.07	.13	.23	.25	.29	.33	.42	.46	.35	.40	.49
2	PU/PBHTS	.047	.06	.13	.30	.58	.78	.80	.62	.57	.58	.52	.55	.67
3	PU/PVC-NBR	.050	.06	.11	.42	.75	.93	.96	.76	.62	.56	.65	.70	.76
4	PU/SBR	.039	.05	.08	.13	.42	.62	.80	.85	.87	.73	.62	.56	.57
5	PU/PVC	.080	.04	.06	.33	.22	.15	.18	.20	.29	.25	.21	.28	.38
6	PU/PMMA	.056	.03	.04	.12	.36	.50	.38	.27	.33	.48	.27	.30	.43
7	PU/fiber glass	.054	.08	.11	.16	.28	.52	.58	.49	.55	.58	.61	.63	.70
8	PU/Pb	.036	.05	.07	.24	.32	.68	.74	.73	.68	.60	.48	.45	.48
		.046	.06	.07	.15	.32	.29	.28	.24	.27	.28	.41	.34	.43
		.107	.04	.07	.23	.15	.15	.16	.15	.21	.21	.19	.22	.29
9	PU/Pb alloy	.050	.05	.06	.13	.40	.42	.44	.55	.65	.45	.45	.53	.62
10	PU/BaSO <sub>4</sub>	.068	.05	.08	.27	.26	.23	.23	.26	.41	.40	.30	.38	.49
11	Scot's Coustex acoustical foam	.039	.08	.15	.30	—	.53	—	—	.85	—	—	.86	—
12	Aquaplas F.70.100 foam	.033	.07	.18	.39	.55	.58	.64	.79	.78	.58	.65	.76	.82
13	PU/PVC-NBR/SBR <sup>a</sup>	.046	.07	.16	.15	.40	.66	.74	.99	.96	.91	.81	.74	.93

<sup>a</sup> Results obtained at 23°C.

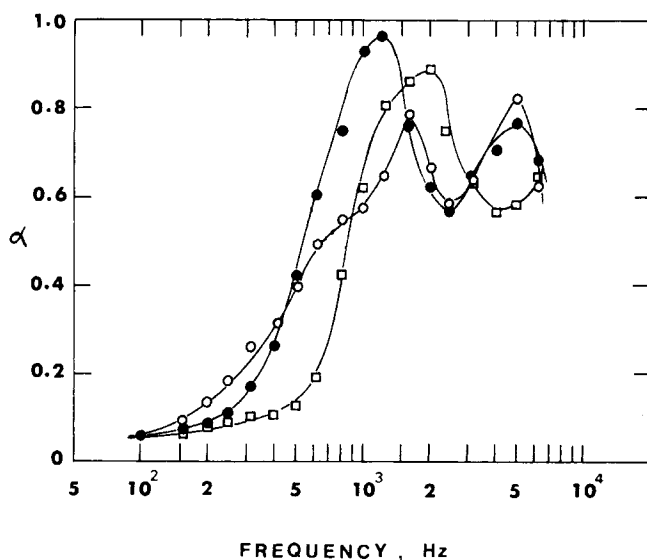


Fig. 6. Absorption of airborne sound by the experimental polyurethane foams compared with that by the commercial Aquaplas F.70.100 foam at 60°C: (O) Blachford's Aquaplas F.70.100 foam; (●) polyurethane/PVC-NBR foam; (■) polyurethane/SBR foam; sample thickness, 25 mm.

are kept nearly constant, sound energy attenuation will be affected mainly by the viscous continuous phase.

Other modifiers were also used such as poly(vinyl chloride), poly(methyl methacrylate), fiber glass, lead powder, lead alloy, and barium sulfate, but they did not improve the sound absorption significantly. This is because the final products were either too dense or too rigid.

The sound absorption capacity of some of the new products is compared with that of a commercial foam in Figure 6. The results for a polyurethane/PVC-NBR foam exceeded those for a commercial foam from 500 Hz to 1500 Hz, whereas those for a polyurethane/SBR foam were greater from 900 Hz to 3000 Hz. The performance of the experimental products can also be rated as a percentage in-

TABLE II  
Ratings of the Polyurethane-Based Foams Relative to Commercial Products

Test frequency, Hz	% Higher than Blachford's Aquaplas F.70.100 Foam			% Higher than Scott's Coustex Acoustical Foam <sup>a</sup>		
	PU/PB <sub>H</sub> TS	PU/PVC-NBR	PU/SBR	PU/PB <sub>H</sub> TS	PU/PUC-NBR	PU/SBR
500		8		0	40	
800	6	36				
1000	35	60	7			
1250	25	50	25	47	76	17
1600			8			
2000			12			3
2500	0		26			
3150		0				

<sup>a</sup> Based on published values for Scott's Coustic Acoustical Foam.

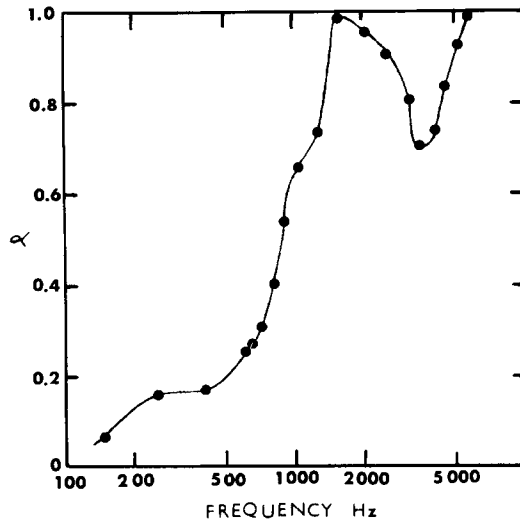


Fig. 7. Absorption of airborne sound by a polyurethane polyblend containing both PVC-NBR and SBR, at 23°C; sample thickness, 25 mm.

crease of the “normal sound absorption coefficient” over the two commercial materials based on values for the coefficient published by the suppliers. This is shown in Table II. The results also suggest that a polyblend containing both PVC-NBR and SBR would be a good sound absorber, as shown in Table I and Figure 7.

The excellent sound absorption characteristics of the experimental products could be attributed only to the ability of the materials to absorb a greater amount

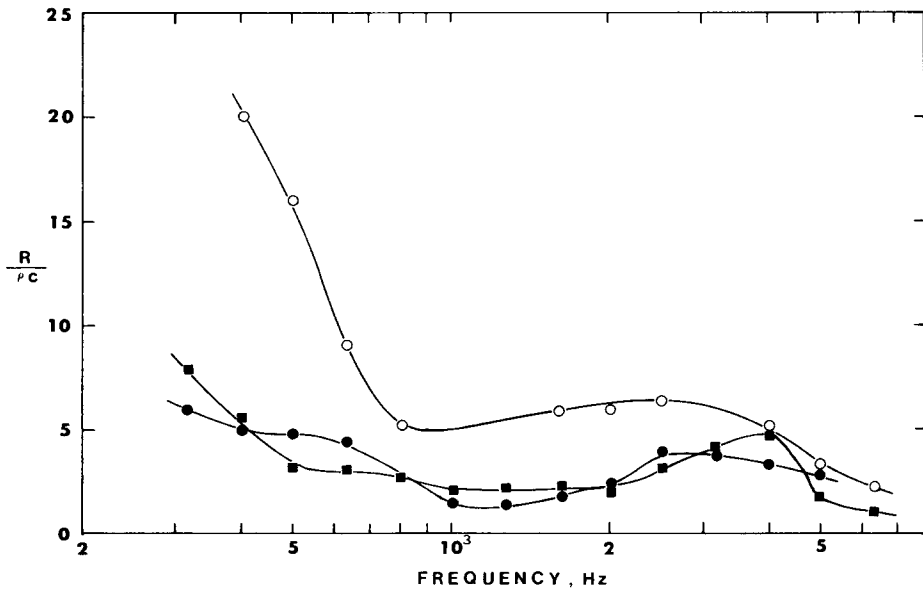


Fig. 8. Specific normal acoustic resistance of polyurethane foam (○), polyurethane/SBR foam (■), and polyurethane/PVC-NBR foam (●); sample thickness, 25 mm; temperature, 60°C.

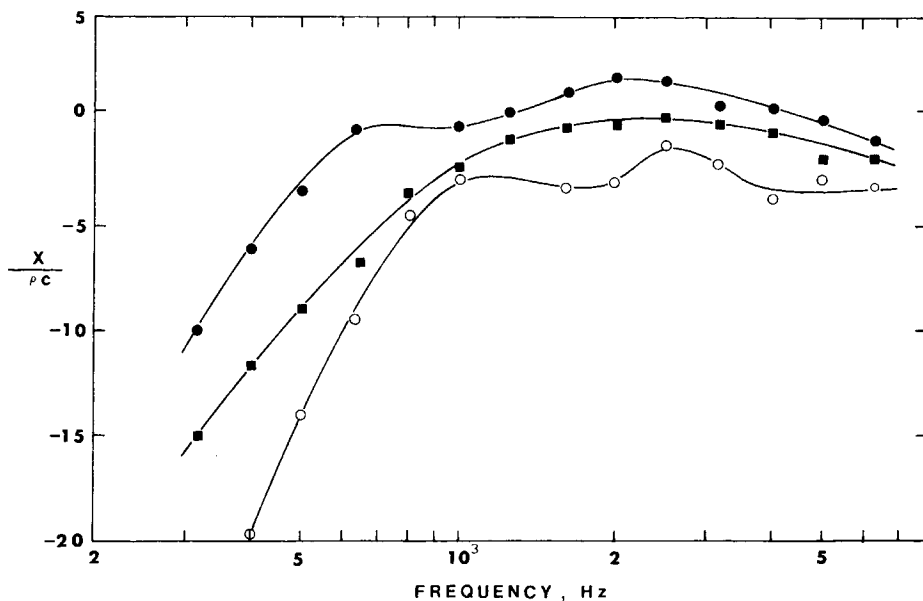


Fig. 9. Specific normal acoustic reactance of polyurethane foam (O), polyurethane/SBR foam (■), and polyurethane/PVC-NBR foam (●); sample thickness, 25 mm; temperature, 60°C.

of acoustic energy. There are other factors to be considered. The foams are closed-cell in contrast to the open-cell structure of the commercial products. The results show that leathery closed-cell foams performed better acoustically than commercially available elastic open-cell foams. It was believed that the less dense or more porous a material, the greater would be sound absorption. This generalization is applicable only to a given material and is invalid for comparing different materials. For example, the polyurethane containing lead powder (Table I) was prepared to three densities, namely, 0.036, 0.046, and 0.107 g/cm<sup>3</sup>. The results show that the lower density grade had a higher absorption coefficient, but different from that of other foams of the same density. Therefore, when two different materials are involved, density and porosity cannot be used as the sole criteria for sound as has been done.<sup>4</sup>

The materials should be grouped in three classes: (a) rigid materials, (b) highly elastic materials, and (c) leathery and "dead" materials. The density and porosity may then play an important role in the sound absorption of the materials within each class. When materials belonging to two different classes are to be evaluated for acoustical performance, the controlling factor will be the chemical composition of the material exhibited by its bulk properties such as its ability to absorb energy and dissipate it as heat. If the material is a foam, the gas phase and the interphase reaction should also be considered. In general, the acoustical absorptive power of foamed materials would be in the following order: class (c) > class (b) > class (a).

The specific normal acoustic resistance and reactance of the polyurethane-based foams are shown in Figures 8 and 9, respectively. It was found that at 60°C, the resistance approached unity and the reactance was small. The molecular segments tend to follow the waves giving rise to a viscous effect. The thin membranes may also follow the impinging sound waves. At medium frequencies,

the acoustic impedance approaches one. This is due to the out-of-phase component, the loss modulus  $E''$ . More acoustic energy would be transformed into heat energy and dissipated within the material. This is shown by the sound absorption characteristics of the foams with absorption peaks near 1000 Hz. However, as the frequency continues to increase, the relaxation time will be too long for either the molecular segments or the thin membranes to move. Thus, the whole system will be more "rigid," and the ability to convert acoustic energy into heat is reduced, and the absorption coefficients are smaller.

### Effect of Morphology on Acoustical Absorption of Polyurethane Foams

The morphology of the foams may be important in acoustic absorption. From the electron microscope studies, it was found that the polyurethane-based foams were closed-cell with very thin membranes connecting the cell walls. The flexural vibrations of the membranes caused by the impinging sound waves would result in acoustic energy loss both by dissipation of heat by viscous damping within the membrane and by interface friction. The thin membranes also permit the transmission of sound into the bulk of the material where the acoustic energy would be transformed into heat. Each thin membrane would act as an acoustically transparent surface with a mass less than  $0.01 \text{ g/cm}^2$ . "Acoustical transparency"<sup>25</sup> is used to denote a relatively free passage of sound through the exposed surface of a material. Moreover, the wave-like or crinkled membranes would cause multiple reflections of the impinging sound waves in addition to the flexural vibrations, thus resulting in greater sound attenuation by interfacial friction.

The vibration damping ability of these materials was studied and the results published separately.<sup>30</sup>

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