Polyurethane Foam Molding Technologies for Improving Total Passenger Compartment Comfort

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ABSTRACT

Improvements in passenger compartment comfort continue to be one of the key needs of the global transportation industry. Since their introduction more than 40 years ago, flexible molded polyurethane foams have successfully contributed to the comfort provided by all forms of transportation seating. Initially required to provide just a wide range of load bearing, seating foams are now being designed for longer service life and better vibration damping and are considered to be a functional part of the overall acoustical package. New performance requirements are being placed on the NVH grade of foams and all interior components of passenger compartments must contribute to a reduction in odor and emissions.

To address the ongoing and newer challenges, The Dow Chemical Company has developed several new chemical technologies that will be detailed in this paper. Specific data will be presented to illustrate new foam chemistries that offer low emissions, reduced density, improved vibration management, noise abatement, durability and processing. Attention will be focused on how the choice of polyurethane raw materials impacts foam resilience, mechanical damping and resonance as well as acoustic absorption and noise transmission.

The results presented in this paper will help foam producers, seat assemblers, acoustic part manufacturers and OEM interior designers in their efforts to further improve the comfort performance of transportation systems based on flexible molded polyurethane foams.

INTRODUCTION

Polyurethane molded flexible foams [1] are key components of automobile interiors and contribute to passenger comfort in many different ways. More than 40 years after their introduction, the foam use per vehicle is still growing worldwide. Indeed, by virtue of their superior vibration damping capability over a wide range of frequencies at low material density, polyurethane foams are found today not only in automotive seats but also in various acoustical parts.

Comfort experience is a combination of many different factors, including aesthetics. During a journey, car occupants are subjected to both mental and physical stresses when exposed to road vibrations, dense traffic, noise and different weather conditions. Polyurethane foams found in seats and in sound insulating packages are instrumental in reducing those stresses. Design for comfort is intimately linked to vibration research. Vibration isolation in the low frequency range by the seat assembly and the attenuation of high frequency vibrations from the running engine, or other sources, transmitted into the passenger compartment, with NVH (Noise, Vibration, Harshness) components, allows the construction of comfortable cars. In addition, polyurethane foams show high durability and perform well from the beginning to the end of a journey and over a vehicle life of more than one hundred thousands miles. OEMs worldwide are relying on flexible polyurethane foams today more than ever to optimize automotive comfort.

The trend towards density reduction whilst maintaining technical performance specifications continues. In addition of that, elimination of all types of chemical emissions and/or odors is becoming an important issue. Dow Chemical is developing new raw materials to respond to these needs.

BACKGROUND

SEATING COMFORT

Human exposure to mechanical vibrations causes fatigue and discomfort. The magnitude of the effect depends on the intensity, duration and directions of the excitation. In seat cushion design, the most important vibration frequency is the "occupant-cushion-seat base" mass-spring-mass system resonance frequency, but the filtering at higher frequencies is important as well. The basic design requirement is to ensure that the resonance motion of the seated person occurs in a frequency range where the force input from the road is low (2-5 Hz) and outside of the body high sensitivity range (4-8 Hz). In practice, for a predetermined load bearing requirement, foam development is striving to shift the body motion resonance to lower frequency. The amplification factor at resonance needs to be kept as small as possible to minimize the total force transmitted to the driver.

In use, the seat foam core is subjected to multi-axial stresses of variable amplitudes and frequencies and the imposed strains may be large. Automotive force transmissibility tests, such as the Japanese Automobile Standards Organization (JASO) B 407-82 test for example, are already a simplification as the applied static force and strain amplitude are constant and a quasi-sinusoidal frequency sweep is applied. In a previous paper [2], we have demonstrated that the resonance frequency of the "Tekken" test assembly (JASO test) and the amplification at resonance are readily approximated by the equations for the damped harmonic oscillator [3] (Figure 1). The foam's cushioning performance is modeled by the combination of a spring with spring constant (k) and a dash pot with damping constant (C). The spring represents the foam dynamic stiffness. The total foam damping capability is the sum of visco-elastic, pneumatic and frictional effects (emphasized separately in the center of the figure).

The steady state solutions for the resonance frequency, f_r, and the amplification factor of vibration at resonance, a_r (also called Transmissibility, Tr), for the model are described by the equations below:

$$f_r = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{M}} \quad (1) \qquad\qquad a_r = \frac{1}{C} \cdot \sqrt{k.M} \quad (2)$$

Thus, for a fixed test assembly, the resonant frequency varies only with the foam dynamic stiffness *k* in the deformed state (from the static weight M). The dynamic stiffness (= foam spring constant, k) is dependent on the foam pad thickness (= length of the spring) and the foam hardness (modulus). To ensure that the resonant frequency is low, the foam should be tuned such that the use defor

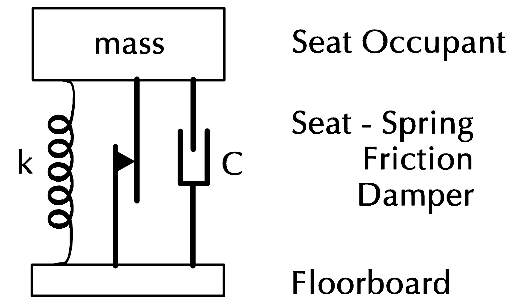

Figure 1: Damped harmonic oscillator model for seat performance

mation is in the plateau of elastic buckling where the dynamic stiffness is near its minimum [4].

The amplification factor (a) is proportional to the foam stiffness and inversely proportional to the damping constant (C). The amplification at resonance a_r is reduced by increasing the foam damping constant (hysteresis loss); higher damping however tends to considerably broaden the transmissibility peak, such that the point where the system becomes vibration isolating is reached later and the damping capacity at high frequency is diminished. In practice, a compromise needs to be sought.

NOISE CONTROL

In the automotive domain, acoustical comfort relates both to the comfort of the passengers and the comfort of the pedestrians and people living close to the traffic. Noise emissions by motor vehicles were set in Europe by the 1995 EU "pass-by" legislation. Comparable regulations are planned in other geographical regions. Interior car noise quality has become a major criterion in the highly competitive automotive market. Because of the inherent ability of polyurethane to produce foams with very different physical characteristics, it has been the material of choice in many applications in Automotive Noise and Vibration Control treatment.

Hirabayashi *and al.* reviewed the mechanistic aspects of NVH control [5]. A noise system can be analyzed in terms of three basic elements: the noise source, the noise transmission path and the receiver. The three dominant noise sources in a car are the drive train, the tires, including suspension system, and the wind. The noise paths are complex but, in principle, sound is propagating through air (airborne sound) or through the car body (structural noise). Polyurethane foams are an integral part of acoustic barriers placed to attenuate the sound wave before it reaches the occupant (receiver). In the cabin, foams act as absorbers reducing the total sound pressure around the passengers.

Sound absorption

The design goal for all soft trim parts in the automobile interior is to provide as much sound absorption as possible. The seats account for about half of the total absorption possible in a typical car [6]. The headliner is the next important absorber. For a seat assembly with a given surface, the sound absorption characteristics depend on the structure of the seat cover materials and the type of foam used inside the cushion and backrest. Cheng and Ebbitt [7] measured noise absorption of seats and covers. Test results showed distinct differences between textiles, leather and vinyl, with cloth seats having superior properties. Foam core densities affected the performance as well.

In this section we will more closely examine foams, with and without skin, and compare the absorption coefficients of different foam chemistries. The aim is to correlate acoustic performance with foam structural parameters, in order to optimize the seat acoustic performance.

The propagation of sound waves through porous media as described by the theory of Biot has been applied to polyurethane foams by Lauriks [8]. Theoretical [8] and empirical [9] models exist, but are complex with respect to input parameters and computing mathematics. The important foam parameters also can be introduced intuitively.

When an airborne sound wave hits a rigid surface, for example a metal sheet or a closed cell rigid foam, it will be reflected substantially, like light in a mirror, and only a minor fraction of the sound energy enters the material. The situation is quite different when the foam cells are open and the air borne wave continues its way into the foam structure. Upon propagating through the pores, the sound pressure is reduced by friction of air against the pore walls and eventually by moving the cell membranes when the foam is sufficiently soft. The longer the wave travels through the foam, the more damping occurs. Therefore, foam thickness is an important parameter of absorption performance. At constant foam layer thickness, the next parameter to optimize is the amount of friction between the medium (air) and the frame (foam skeleton). Intuitively, it can be felt that pore diameter or flow resistivity will play a determinant role. To transfer energy from the medium to the skeleton, the frame modulus should be sufficiently low, which is the case with soft foam (measured by IFD, CFD for example); and the surface interaction should be large.

The absorption coefficient α of a material is defined as:

$$\alpha = 1 - [R_r/R_i] \qquad (3)$$

with R_i = incident sound wave pressure
R_r = reflected sound wave pressure

It can be understood that the absorption increases: as the amount of accessible pores increases i.e. with increasing acoustic porosity or open cell content and within certain ranges, increases with decreasing pore diameter (D) or increasing flow resistivity and finally is influenced by the frame flexibility.

Interestingly, these foam parameters have been historically measured and used to characterize foams (open cell content, airflow and load bearing). In this paper, we will correlate such parameters with the absorption coefficient measured for different foam chemistries.

Sound Transmission

Barrier materials are positioned in the noise path to reduce the amplitude of the sound waves propagating in a certain direction. In automotive application, sound absorbing foams are in contact with the metal shell to reduce the amount of noise entering the passenger compartment. The effectiveness of a material as a barrier is measured by the Transmisson Loss (TL). The transmission loss is the difference in sound intensity before (Ii) and after (It) the barrier expressed in dB:

$$TL = 10 \log Ii/It \qquad (4)$$

The transmission loss is not a foam property as such, but is the performance of a sandwich structure consisting of a metal sheet and a heavy layer with a foam core. In this study we have used the “Petite Cabine” as acoustic transmission screening tool (see Experimental). The foam performance is characterized by its Insertion Loss (IL) defined as:

$$IL = TL(\text{with composite}) - TL(\text{empty system}) \qquad (5)$$

The acoustic performance of the composite is governed by the mass law, which determines the basic shape of the IL curve. On the base curve, structural (mass-spring-mass) and cavity resonances are superimposed, which are inherent to the construction of the measuring chamber [10]. The insertion loss performance increases with increasing septum mass and increasing foam thickness [11], which is contrary to the volume and weight saving objectives in automobile design. Polyurethane foam cores, by their energy dissipating mechanisms, allow for considerable weight and volume reduction in the vehicle while maintaining good acoustic performance.

EXPERIMENTAL

Foam Preparation

Bench scale molded foams were produced in a 30x30x10 cm test block style mold heated at 55^0C using the standard hand-mixing procedure [1]. High pressure impingement mixing machines were used to pour foams in a 40x40x10 cm standard test block style mold and in a variety of production seat molds. Foam formulations are indicated within each section of the paper.

Foam physical property testing

Basic foam physical properties were determined in accordance with ASTM, ISO, DIN, NF and major OEM test procedures. Tropical dynamic fatigue tests were carried out at 40°C and 80 % RH as described in a previous paper [12].

Crushing force and hot IFD's

A simple test was carried out to measure the foam tightness at demold and the level of foam curing. The foam pad was demolded with precautions and one minute after demold was indented at 50 % deflection. This value in Newton is referred to as the "Crushing Force" (CF) Then the foam was passed through a roller crusher to open all the foam cells and the pad was again measured for IFD hardness at 50 % deflection. This second value, referred to as "Hot IFD" in Newton, gives an indication of the level of foam curing. Obviously, the higher the CF, the tighter the foam, and the higher the Hot IFD, the better this foam is cured.

Vibration testing

Vibration tests at low frequency (1-10 Hz) were performed according to the Japanese Automobile Standards Organization (JASO) B-407-82 method on a Itoh Seiki, Model C-1001-DL vibration table. Displacement amplitude transmissibility versus input frequency is recorded. Additional vibration studies were performed with a Material Test Systems (MTS) Model 831 servo-hydraulic load frame, equipped with TestStar II electronic controls and a Radicalor environmental chamber (23°C; 50 %RH). Test procedure: 100x100x50 mm samples; static load 40N, dynamic load amplitude 10 N; frequency sweep from 1 to 10 Hz in steps of 0.25 Hz.

Acoustic testing

Normal incidence sound absorption coefficients were measured between 100 and 5000 Hz with a two microphones impedance tube according to ASTM E 1050 (Brüel & Kjaer 4206). This method utilizes a hollow tube, which is equipped with a speaker at one end and a sample holder at the other. Plane waves are generated in the tube by a random noise source, and the decomposition of the standing wave is achieved with the measurement of acoustic pressures at two fixed locations close to the sample using wall-mounted microphones. Using a digital frequency analysis system, the complex acoustic transfer function of the two microphone signals is determined and used to compute the normal incidence absorption of the acoustic material. Air Flow Resistance measurements were made with the AFM 80 Instrument from Norsonic Brechbühl according to DIN 52 213. Insertion losses were measured with the Petite Cabine. This test was developed by Renault and is used to expediently measure insertion loss for a variety of insulators, which are usually employed as dash or floor insulators. The test equipment essentially consists of a concrete base with nine loudspeakers, the excitation chamber, separated by a metal frame with a 0.8mm steel metal sheet to accommodate the 700x700x20mm test sample from a semi-anechoic hood with a microphone, the receiving chamber. The semi-anechoic hood prevents reflection of the transmitted sound energy. The loudspeakers are excited with a filtered white noise to produce a sound pressure level of about 80 dB from 100 to 5000 Hz in the receiving chamber with the sheet metal panel.

The Petite Cabine test is conducted by first measuring the sound pressure level (from 100 to 5000 Hz) produced in the upper chamber with only the sheet metal panel installed. Next the insulator material consisting of the damping material and a 5 kg/m^2 heavy layer is installed, and the test repeated. By subtracting the levels measured with the test material installed from those measured with the bare panel, the insertion loss (IL) in dB of the insulator is determined.

PVC Staining/Aging

Accelerated aging tests at elevated temperature were carried out in closed containers in the presence of a PVC (PolyVinyl Chloride) foil. A foam sample of 50x50x50 mm was cut from the core of the molded foam pad and placed at the bottom of a one liter glass jar. A piece of gray PVC skin, reference E 6 025 373A0175A, supplied by Benecke-Kaliko, was hung with a Chromium-Nickel alloy-based string supported by the rim of the jar, which was then sealed. Aging was carried out at 115°C for 72 hours. After cooling, the PVC sheet discoloration was measured using a Minolta Chroma Meter CR 210. The smaller the change in color, the lower the Δ E measured in this test.

RESULTS AND DISCUSSION

A) SEATING COMFORT

Polyol developments

In 1994, Dow introduced novel polyols, which were developed for cold cure TDI and TDI/MDI blend High Resilience (HR) molding [13, 14]. Based on higher functionality initiators than those used at that time, the new generation high functionality (HF) polyols were designed to give better foam cure at demold, higher foam resiliency, and better durability.

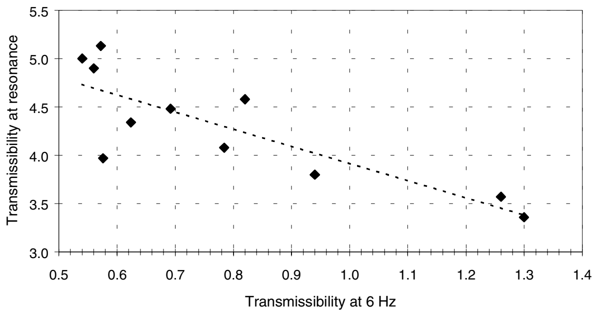

Figure 2: Effect of the Transmissibility at resonance (a_r) on the Transmissibility at 6 Hz (TDI/MDI based foams, density: 50 kg/m^3, hardness: 20-22 kgf/314 cm^2 at 25% indentation) in the JASO test.

TDI-based foams produced with these HF polyols were evaluated in the Pressure Distribution Test and the Seat Occupied Vibration Test [15]. In the first test, it appeared that foams based on HF polyols gave better pressure distribution than foams based on traditional materials, which is known to be essential to the comfort of the seat. In the vibration test, however, it was found that HF polyols did not show any significant difference versus conventional polyols used in high resilience formulations.

Foam thickness, foam hardness and foam resilience are the main parameters which determine the general shape of the force/displacement transmissibility curve. When the foam thickness is increased, the mass-spring-mass resonance shifts to lower frequency. In the model of the harmonic oscillator, this corresponds to reducing the spring stiffness by making the spring longer. However, increasing the foam pad thickness is limited from a designer's standpoint, since it reduces the passengers' space in the car. Foam modulus directly impacts the spring constant. Globally, softer foams (lower k) exhibit a lower resonant frequency. But, considering the range of typical OEMs' hardness specifications from 15-28 kg/314 cm^2 at 25% deflection- the achievable resonance shift range is narrow and considerably restricts foam hardness as a design tool. Yet, it remains important to tune the foam hardness such that the cushion's dynamic stiffness is minimized under the actual use deformation. Foam resilience is associated with the damping constant (C) and impacts the transmissibility curve such that with increased damping the amplification at resonance is reduced but the resonance peak is broadened. As a consequence the vibration damping capacity at high frequency is reduced and the point at which the system becomes vibration isolating (Transmissibility <1) is often reached later. Thus, the model predicts that high resilient foams yield a higher amplification at resonance but become vibration isolating earlier. This effect is illustrated in Figure 2, where data from the JASO test are collected from previous tests and the amplification factor at resonance is plotted against the transmissibility at 6 Hz: the higher the amplification factor at resonance, the more damping at 6 Hz. All of these foam pads had resonance frequencies between 3.2 and 3.6 Hz measured with a thickness of 10 cm.

Although our first generation polyols for HR molding developed in the early 90's were suitable for most OEMs' requirements, foam resilience was still borderline for some of those calling for ball rebound of 70% or higher.

Table 1 : Polyol Analytical Data

Polyol	A	B
Calculated Functionality*	3.0	3.2
EW	1810	2150
Viscosity at 25^{0}C (cSt)	1250	1530

* calculated from the initiator functionality, the hydroxyl number or EW and the level of unsaturation (monol).

Table 2: Physical Properties (foam index 100, density 45 kg/m^3)

Isocyanate		TDI	TDI	TDI/MDI	TDI/MDI
Polyol		A	B	A	B
Hardness. IFD 25%	Kg	20.5	20.0	20.0	19.0
Hysteresis Loss	%	21.1	18.9	19.7	18.2
Tear Strength	N/m	325	315	260	215
Tensile Strength	kpa	160	145	120	205
Elongation	%	125	135	95	135
Foam Resilience	(%	65	70	68	74
Dry C-Set (50%)	%CT	6.3	3.3	5.6	3.1
Wet C-Set (50%)	%CT	10.6	9.4	19.3	11.7
Humid Aged C-Set (50%)	%CT	6.1	4.7	13.9	11.4

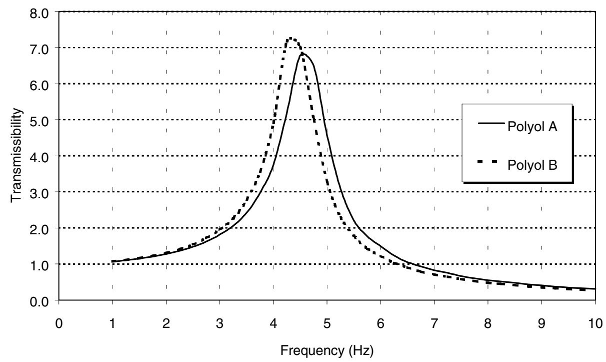

Figure 3: Vibration Curves (MTS test) for TDI/MDI (TM20) HR Foams (Polyols A & B)

Therefore, Dow developed second generation polyols aiming at HR molded foams with very high resiliency and further improved physical properties [16]. Polyol A and Polyol B, in Table 1 and Table 2, refer to the first and second generation polyols, respectively. Both with TDI and TDI/MDI blends, the foams made with polyol B show higher resilience than the one produced with polyol A. It is likely that the increase in ball rebound is associated with the higher equivalent weight (EW) of the polyol B yielding a more elastic foam with lower hysteresis loss. In addition, the optimization of the polyol structure calls for the improved physical properties listed in Table 2.

Vibration performance simulation was also performed on the MTS servo-hydraulic frame with samples taken from molded foam pads at density 45 kg/m^3 that had been made successively with polyols A and B. An example thereof relating to TM20 foams is shown in Figure 3. It is typical for these high resilient foams to exhibit a relatively high transmissibility at resonance (amplification factor 6-7 at 4.5 Hz), but to become rapidly vibration isolating between 6 and 7 Hz. The slightly softer second-generation foam B has the lowest resonance frequency and a slightly higher amplification, in accordance with the resilience data.

Isocyanate developments

In a previous paper [12], we have shown that in a typical dynamic fatigue test which ran for 15-20 hours, the foam height and load loss have already reached their final values after the first few hours of the test. For instance, a foam which gives 25% load loss after 15 hours has already reached 20% load loss after a 4-hour test. Although the dynamic fatigue test usually reflects the durability performance of the foam, it can also be considered indirectly as a comfort test, since, during a long journey in a car, it is desirable for the driver and for the passengers if the seat (Hip) H-point [17] change remains as low as possible.

In a tropical dynamic fatigue test, it was found that the performance of hot cure molded foams in terms of height and load loss is generally better than that of cold cure foams, and among cold cure foams, MDI HR molded foams are better than TDI or TDI/MDI foams (Table 3). This is why the MDI technology is commonly used for making foams required to meet drastic tropical dynamic fatigue tests. On the other hand, the major drawback of MDI based HR molded foams has been the limitation in density reduction due to poor flowability in complex molds and to the negative effect of increased water level on processability and foam durability properties [18]. Recently new isocyanates and improved polyol formulations have allowed a significant improvement in density reduction while maintaining foam durability [19].

Table 3: Comparison of the performance of different foams in theTropical Dynamic Fatigue test (foam density: 45 kg/m^3)

Foam Chemistry		Hot cure	TDI	TDI/MDI	MDI (current)	MDI (new)
Height loss	%	3.8	4.4	6.1	3.4	3.5
Load Loss	%	18.6	26.0	29.8	21.3	16.9

Table 4: MDI HRM Foam physical properties

		Isocyanate A	Isocyanate A	Isocyanate B	Isocyanate B
Part weight	g	639	595	641	598
Molded density	Kg/m^3	50.1	46.6	50.2	46.9
IFD 30 mm	N	240	210	226	200
BMW tropical fatigue					
Height loss	%	2.6	2.5	3.3	4.1
Load loss	%	7.5	7.4	10.8	9.1
Corrected load loss	%	16.3	15.7	20.2	20.5
Peugeot fatigue					
Height loss	%	3.3	3.0	4.4	4.0
Load loss	%	14.3	16.1	11.1	12.0

Table 5: Vibration MDI HR Molding (pads75 mm thickness, JASO test)

		Isocyanate A Polyol A	Isocyanate A Polyol B
Foam density	kg/m^3	56.0	55.5
CFD (40%)	kPa	8.4	7.8
Foam Resilience	%	60	58
Resonance frequency	Hz	4.3	4.7
Transmissibility at resonance		4.3	4.3
Transmissibility at 6 Hz		1.2	1.7

Table 4 shows the physical properties of 60mm thick front seat pads made with Isocyanate A and Isocyanate B meeting Peugeot fatigue and BMW tropical fatigue specifications at low densities. These foams were made on a high pressure machine in a mold kept at 55 °C and were demolded 3.30 minutes after pouring. Isocyanate index was 85.

The data show that Isocyanate B gives slightly softer foams than Isocyanate A while Peugeot dynamic fatigue properties are superior. By contrast, Isocyanate A yields very good BMW tropical fatigue results. It is important to point out here that all of these foams meet BMW and Peugeot hardness targets for front seats.

Similar foams were tested for resonance frequency and the data are collected in Table 5. The advantage of these foams is that the transmissibility maximum at resonance is lower compared to TDI based high resilient foams, such that less energy is transmitted to the driver going through the resonance motion. But, because the transmissibility peaks are broader, they become vibration damping only after 6 Hz.

Whilst the present paper is focusing on vibration performance of foams between 0 and 10 Hz, a study has already been published on seating foam behavior until 80 Hz [12].

In summary, new polyols and isocyanates have been developed by Dow to broaden the range of possibilities available to foamers aiming to adjust foam vibration properties at low frequencies whilst maintaining superior durability performance. The performance at high frequencies of seating foams is also an important factor contributing to the acoustical comfort of a vehicle as will be discussed in the next section.

B) ACOUSTICAL COMFORT

Absorption

The four main seating foam technologies were examined for acoustic absorption as a function of frequency in the standing wave apparatus. Some key physical properties of the foams are collected in Table 6 and the absorption curves of the foam cores are displayed in Figure 4. The absorption curves of all the foams show high efficiency. The shape of the sound absorption curve is mainly governed by the airflow resistance: open foams show initially less absorption but better performance at high frequency. Foams which are more closed exhibit a higher slope in the low frequency range, but are less effective absorbers at high frequency.

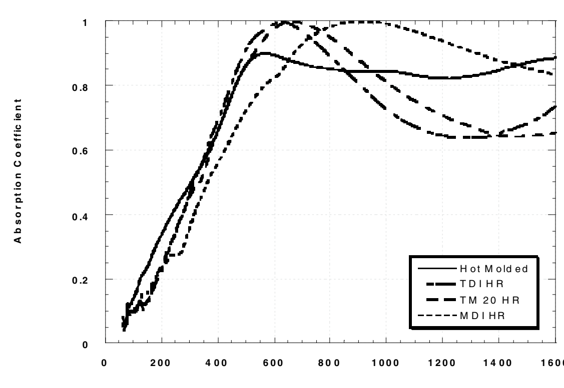

Figure 4: Sound Absorption for 60mm thick core samples

Table 6 Physical Properties of Foams Tested for Sound Absorption

Foam:			Hot Molded	TDI HR	TM 20 HR	MDI HR
CFD (40%)	kPa		8.0	4.0	4.0	7.0
Flow resistivity	$N.s/m^4$	Core	34'000	7'600	7'000	9'000
		with Skin	86'000	8'500	7'500	11'000

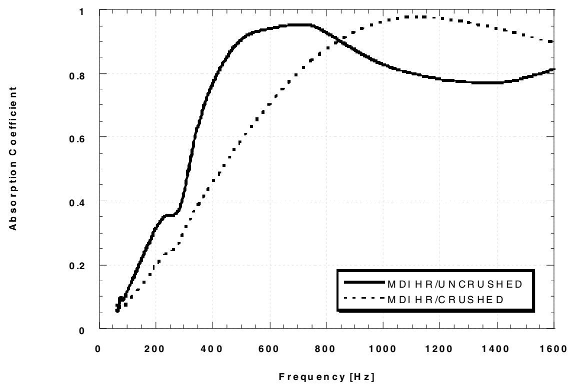

Figure 5: Effect of Crushing on Sound Absorption

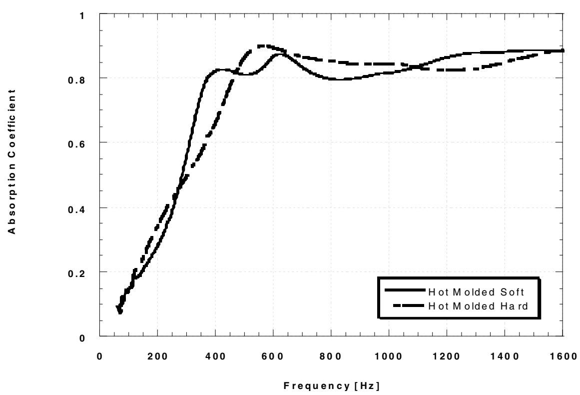

Figure 6: Effect of Hardness on Sound Absorption

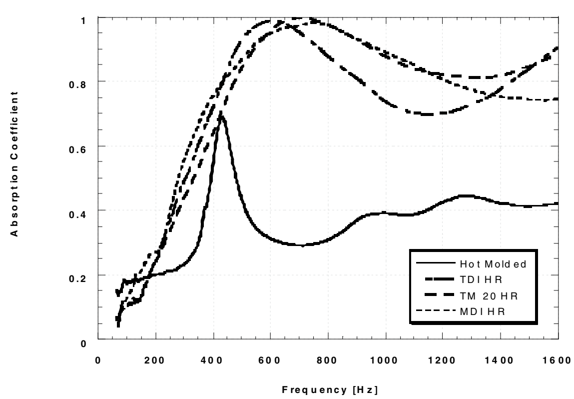

Figure 7: Sound Absorption for 60mm thick samples with skin

This general trend is confirmed by Figure 5. Crushing the foam decreases its airflow resistance by a factor of 2.5 and causes only a 10 % reduction in foam hardness, but markedly decreases the initial slope of the sound absorption curve and shifts the absorption maximum to higher frequency. Foam hardness globally has a limited influence on the sound absorption coefficient as demonstrated by Figure 6. The initial part of the sound absorption curve of a 3 kPa CFD 40 % hot molded foam is not so different from that of a 8 kPa, while the absorption maxima clearly differ in detail. The absorption characteristics after the first maximum are governed by the interference of the sound wave reflected from the surface of the sample with the sound wave reflected from the back of the impedance tube. The curves from the TDI HR and the TM 20 HR foams show the largest amplitude fluctuation (interference pattern), indicating a higher intensity of the two sound waves; such foams exhibit lower sound absorbing capacity. The curve from the hot molded foam is relatively flat, indicating a higher sound absorption.

A completely different situation is created when the foam specimens are tested with skin (Figure 7). Thus, in principle, a two-layer composite is formed, especially for the hot cure foams. The skin behaves like a semi-impervious membrane applied to the foam, such that a strong absorption maximum is observed at low frequency with deterioration of the absorption at higher frequency. HR foams with much thinner and more permeable skin, as indicated in Table 6 by the very small difference in the airflow resistance between the sample with and without the skin, show this effect to a lesser extent. It should be remembered that during seat fabrication, when the fabric is added, similar effects are created [7, 20]. In summary, all foam chemistries show comparable acoustic absorption, provided that the processing is well-controlled and the right cell openness is achieved.

Transmission

Mid 90's, Dow introduced a novel polymeric MDI, SPECFLEX* NS 540. This isocyanate was designed to produce foams at a reduced density and faster demold compared to prepolymers in use at that time. Since the introduction of SPECFLEX NS 540, the trend to lower the molded densities continues. Density reduction technology using an auxiliary blowing agent such as carbon dioxide has been developed. This approach is interesting as it does not have a significant impact on the Insertion Loss (IL) [21]. But, when density reduction is achieved by increasing the water level in the formulation, the IL can be affected as shown in Figure 8. Comparing the IL of two foams based on the same polyol and isocyanate with 3.2 and 4.2 % water respectively.

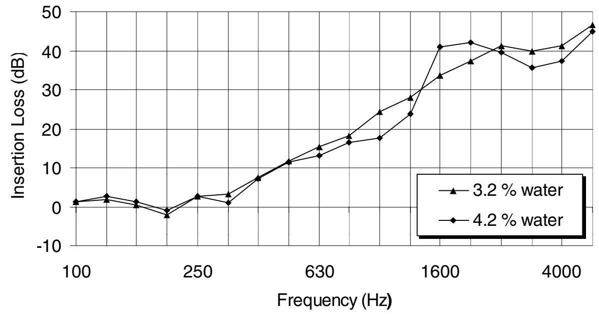

Figure 8: Effect of water content on Petite Cabine IL

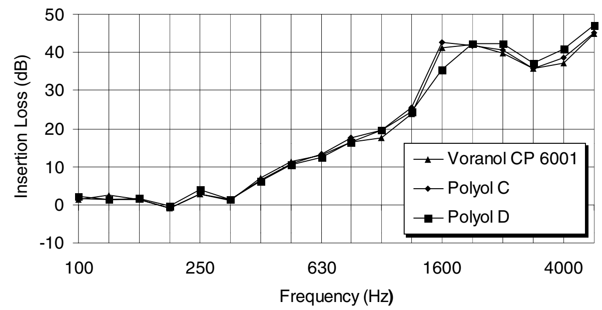

Figure 9: Petite Cabine IL of foams based on SPECFLEX NS 540

The formulations were adjusted to give similar compression hardness. The foam with the higher water level clearly shows a degradation of the IL in the 500–1250 Hz range and an improvement in the 1600-2000 Hz range.

In order to match the higher passenger comfort demands and to comply with the new legislation, the OEMs need more effective sound insulation packages. Weight reduction is an ongoing trend in the automotive industry as weight is directly related to fuel efficiency. For cost reasons, part weight reduction by increased water content is still the most generally adopted solution. As the emphasis has now shifted from the aim of simply reducing the interior noise toward designing a quality interior noise or a car sound signature, Dow has focused on evaluating the impact of the polyol and of the isocyanate in this area of the acoustic performance of HR foams.

Polyol developments

The main polyols parameters influencing foam mechanical performance include equivalent weight, functionality and primary hydroxyl content. In this study, primary hydroxyl content was kept constant to maintain optimum processing. In a density reduction effort, lower polyol functionality and equivalent weight were examined. Using VORANOL* CP 6001 triol as the reference, reduction of the polyol functionality (Polyol C) or equivalent weight (Polyol D) yielded foams with comparable IL as shown by Figure 9.

The choice of the polyol does not seem to have a decisive influence on the acoustical properties of the produced foam. However, given the high complexity of the NVH parts, the choice of the polyol is critical in ensuring the processing necessary to achieve the desired low density and the wide processing latitude to accommodate the different tools of a molding line. With increased water level, these key characteristics are even more difficult to obtain and Dow has optimized polyol structures and formulations to produce low density foams at high water level.

Isocyanate developments

Since the introduction of SPECFLEX NS 540, the PMDI-based technology has been widely accepted in the NVH market as a cost-effective alternative to the prepolymer-based technology. As the need for low density and better acoustic foam grows, Dow is developing new MDIs to recover the acoustic performance and the processing latitude lost with the incremental increase of the water content in the formulation. The effect of the PMDI composition on the insertion loss has been investigated.

With the formulation based on VORANOL CP 6001, replacing SPECFLEX NS 540 by Isocyanate C or Isocyanate D produces a significant increase in the insertion loss in the 1000 to 1600 Hz bands. As opposed to SPECFLEX NS 540, insertion losses of these experimental isocyanates level off above 1600 Hz. With this formulation, the acous-

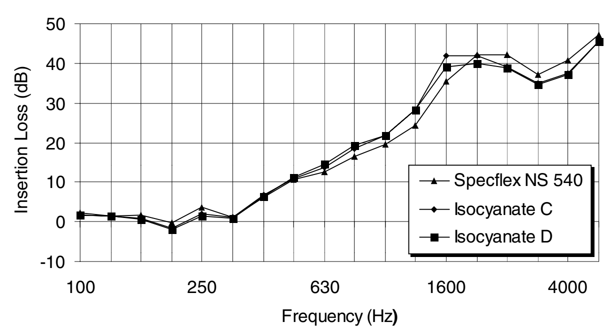

Figure 10: Petite Cabine IL of foams based on Polyol D

tic performance of the foam produced with the two experimental isocyanates is not significantly different. Reducing the functionality of the polyol formulation also reduces the difference between the tested isocyanates and no significant trend can be observed. With the Polyol D based formulations, a trend similar to the one observed with VORANOL CP 6001 based formulations can be observed but the domain with improved IL is extended toward the lower frequency range. Figure 10 shows typical results observed when replacing SPECFLEX NS 540 by the experimental isocyanates.

To conclude, polyurethane formulations can be adjusted in many different ways to produce foam having the desired properties. Some of the formulation variables have been presented and analyzed with the aim of evaluating their effects on the acoustic performance of the final foam. The data presented show that by carefully choosing the polyol and isocyanate composition we can selectively influence the acoustic performance of the foam. This is a first step in designing an acoustic package providing the desired car acoustic signature.

C) EMISSION OF VOLATILE CHEMICALS

After the polyurethane foam industry successfully eliminated the CFC blowing agents from seating formulations worldwide during the late 80's, it embarked in a thorough program to reduce and even eliminate all volatile chemicals coming from the PU foams. Today new low fogging surfactants are widely used [22]. Most additives, flame retardants, antioxydants, are designed not to migrate or leach. The next challenge being addressed at the beginning of this new millenium is the elimination of amine catalyst vapors.

The reduction of the emissions coming from the amine catalysts has been addressed by the catalyst suppliers who have developed non-fugitive alternatives to conventional catalyst systems [23, 24]. These studies have confirmed that it is possible to produce foams with amine catalysts containing isocyanate-reactive hydrogens. However several limitations have been identified: to obtain the desired reactivity profile, relatively high levels of such catalysts must be used and it has been shown that this is detrimental to the PVC staining resistance of such systems. As they are not as selective as the conventional catalysts, it is more difficult to control the blow/gel reaction balance. It has also been found that with some reactive catalyst systems, the formulated polyol blends tend to lose their reactivity over time, especially their curing ability. Another way to eliminate the emissions coming from the amine catalysts is to attach the catalytic site to one of the major components of the foam. This approach ensures that the catalyst is effectively incorporated in the polymer structure. This has been achieved by reacting the catalyst with a trifunctional polyether polyol [25]. Another solution is to use a molecule containing a dialkylamine group separated from the starter unit by a $(CH_2)_n$- group where n has to be equal to or greater than three [26]. These two approaches stress that to be active the catalytical site should not be sterically hindered by the polyether chain.

Table 7: Machine-made foams with conventional amine catalysts and new autocatalytic polyols
(foam density: 45 kg/m3, demold time 3.5 minutes)

Type of polyol		Conventional	Polyol E	Polyol F
VORANOL CP-6001 + VORANOL CP-1421	php	100	50	90
Polyol E		-	50	-
Polyol F		-	-	10
Water		4.3	4.3	4.3
Crosslinker		0.45	0.45	0.45
Conventional amine catalysts		0.4	-	-
Reactive amine catalysts		0.3	0.2	0.3
Surfactant		0.5	0.5	0.5
Isocyanate A		66.9	66.9	66.9
Cream time	s	9	11	10
Gel time	s	73	88	66
Rise time	s	120	95	83
Free rise density	kg/m^3	31	38	30
Crushing Force	N	610	245	760
50 % Hot IFD	N	180	240	285
PVC staining test				
Δ L (black)		- 17.7	+ 0.3	- 0.5
Δ a (red)		+ 9.4	- 0.6	- 0.9
Δ b (yellow)		+ 4.5	+ 2.6	+ 6.5
Δ E		20.5	2.6	6.6

At Dow we found a new route to produce polyols with catalytic activity having various functionalities, equivalent weight and primary hydroxyl levels. Table 7 illustrates typical foam formulations based on some of these new polyols and demonstrates that very good foam processing, including foam curing, is obtained with the combination of these new polyols and relatively low amounts of reactive catalysts. Hence low PVC staining results are obtained. In opposition to polyol formulations based solely on reactive amine catalysts, these formulations show very good stability with time in terms of foam curing. No finger marking was observed at demold on foams made from a three-week-old formulated polyol blend. Under the same conditions, a formulated polyol blend with the same reactivity profile, based only on some specific reactive amine catalysts, already shows marking after one week's storage. Data from Table 8 illustrate that foams made with a combination of these new polyols and a small amount of new reactive amine catalysts give no PVC staining while their physical properties are comparable to those obtained from foams prepared with a high level of similar reactive catalysts and conventional polyols. They also indicate that PVC staining tends to improve with increased isocyanate index. The present study confirms that the autocatalytic polyols developed by Dow for both seating and NVH foams complement the reactive catalysts recently introduced on the market since they address some of their weaknesses. Indeed, by combining these new catalysts with Dow's autocatalytic polyols it is now possible to get good foam processing with almost no PVC staining.

CONCLUSION

To address the ongoing and newer challenges of automotive passenger compartment comfort, new polyurethane raw materials are needed. As it has been shown in this paper, both polyols and isocyanates have to be tuned to meet the requirements of density reduction, elimination of volatiles and improved durability. The Dow Chemical Company is actively working with the industry to respond to these requirements.

Table 8: Comparison of physical properties of foams made with reactive amine catalysts and autocatalytic polyol (isocyanate blend TDI/MDI, VW test methods)

Foam type							
Reactive catalyst package		A	A	A	B	B	B
Amine level	php	0.95	0.95	0.95	0.5	0.5	0.5
Polyol E		-	-	-	54	54	54
Isocyanate index		90	100	105	90	100	105
Core density	kg/m^3	58.0	60.1	62.6	54.1	57.5	56.1
CFD (40%)	kPa	3.0	5.2	8.0	4.1	5.7	6.7
Tensile Strength	kPa	98	129	146	78	125	131
Elongation	%	110	110	105	109	108	94
Tear strength	N/m	147	187	224	158	212	217
Foam Resilience	%	60	64	61	63	63	60
Airflow	cfm	2.2	1.7	2.1	2.7	2.4	2.3
Dry C-Set (50%)	%CT	5.2	3.8	3.8	3.7	3.9	4.1
Heat aging							
Tensile Strength	kPa	98	136	177	77	142	127
Elongation	%	117	108	106	115	109	106
CFD change	%	- 0.8	0.8	- 2.2	- 6.0	- 5.7	-5.0
Humid aging							
Tensile Strength	kPa	88	120	150	84	132	139
Elongation	%	177	165	157	184	153	151
CFD change 1st	%	- 23.6	- 14.7	- 14.4	- 30.2	- 24.4	- 23.0
CFD change 2nd	%	- 35.8	- 31.0	- 31.7	- 39.8	- 37.8	- 37.5
CFD change 3rd	%	12.2	16.4	17.3	9.7	13.4	14.5
Humid Aged C-Set (50%)	%CT	10.8	8.4	8.8	6.4	7.2	7.4
PVC staining							
Δ L (black)		- 2.8	- 1.9	- 0.8	+ 0.35	+ 0.27	+ 0.19
Δ a (red)		+ 1.0	+ 0.3	+ 0.8	- 0.53	- 0.23	+ 0.09
Δ b (yellow)		+ 8.4	+ 6.9	+ 5.6	+ 1.9	+ 0.92	+ 0.07
Δ E		8.9	7.1	5.7	2.0	0.98	0.22

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REFERENCES

1. Herrington, R., De Genova, R., Casati, F. and M. Brown (1997), "Molded Foams" in *Flexible Polyurethane Foams*; Herrington, R. and K. Hock, eds., The Dow Chemical Company, Form No. 109-01061, 11.1-11.41.
2. Casati, F.M., Herrington, R.M., Broos, R. and Y. Miyazaki (1997), "Tailoring the Performance of Molded Flexible Polyurethane Foams for Car Seats", *Proceedings of the 1997 SPI Polyurethanes World Congress;* Technomic: Lancaster, Pa., 402-420.
3. Muster D. and R. Plunkett (1960), "Isolation of Vibrations", Ch. 18 in *"Noise Reduction"*; L. Beranek Ed., McGraw-Hill Book Company.
4. Hilyard N.C., Lee W.L. and A. Cunningham (1991), "Energy Dissipation in Polyurethane Cushion Foams and its Role in Dynamic Ride Comfort", *Cellular Polymers (Conference), Forum Hotel, London UK, 20-22 March 1991*; RAPRA Technology Ltd, 187-191.
5. Hirabayashi T., McCaa D.J., Rebandt R.G., Rush P. and P. Saha (1999), "Automotive Noise and Vibration Control Treatments*", Sound and Vibration, April*, 22-32.
6. Wentzel R.E.and E.R. Green (1997), "Assessing Headliner and Roof Assembly Acoustics", 97126, *SAE International Proceedings of the 1997 Noise and Vibration Conference, Traverse City, MI.*
7. Chen P. and G. Ebbitt (1998), "Noise Absorption of Automotive Seats", 980659, *SAE International Congress & Exposition*, *Detroit, Michigan, February 23-26,* 117-121.
8. Lauriks W. (1994), "Acoustic Characteristics of Low Density Foams" Ch 10 in *"Low Density Cellular Plastics, Physical Basis of Behavior",* Hilyard N.C. and A. Cunningham Eds., Chapman and Hall, London.
9. Voronina N. (1999), "Comparison between Theoretical and Empirical Models for Elastic Porous Materials", *Applied Acoustics*, 58, 255-260.
10. Tang W.C., Zheng H. and C. F. Ng (1998), "Low Frequency Sound Transmission Through Close-fitting Finite Sandwich Panels", *Applied Acoustics*, 55 (1), 13-30.
11. Ling M.K., Hilyard N.C. and A. Cuningham (1991), "Fundamental Studies of the Acoustic Behavior of Foam Backed Floor Covering", *Cellular Polymers (Conference), Forum Hotel, London UK, 20-22 March 1991*, RAPRA Technology Ltd.
12. Casati F.M., Herrington R.M., Broos R., Miyazaki Y., Phan Thanh H. and D. Cadolle (1998), "Automotive Seating Foams: Improving their Comfort and Durability Performance", *Proceedings of the Polyurethanes EXPO'98*, Technomic: Lancaster, Pa., 417-431.
13. Noakes C., Brown M.J., Duff A.W and S. Pique (1994), "Cost-effective Flexible Molded Foams for Car Interiors", *Conference Book of Papers Utech 94*, Automotive, Paper 4.
14. Khameneh K.N., Cosman J.P. and G.D. Hunter (1994), "A New Generation of High Productivity Polyols for HR Molded Foams", *Proceedings of the 1994 SPI Polyurethanes World Congress,* Technomic: Lancaster, Pa., 253-260.
15. McEvoy J., Thakurta K., Pique S and J. Bladon (1996), "Extra-High Resilience, TDI-based, Polyurethane Flexible Foams for High-Comfort, High-Durability Automotive Seating", *Proceedings of the 1996 SPI Polyurethanes World Congress;* Technomic: Lancaster, Pa., 504-511.
16. Berthevas P., Phan Thanh H., Pique S. and Y. Miyasaki (1999), "Recent Advances in Flexible Molded PU Foams for Car Seats", UTECH Asia '99 Conference Book of Papers, Automotive, Paper 1.
17. Brown M.J. (1992), "High sag Factor Foams Boost Comfort and Performance of Car Seats", *Proceedings of the SPI-34th Annual Technical/Marketing Conference*, Technomic: Lancaster, Pa., 463-467.
18. Thoen J., Elwell R., Sewell R., Pellacani L., Pedroni L. and G. Bergianti (1991),"Replacement of Chlorofluorocarbons in all MDI Automotive Seating Foams", *Proceedings of the Polyurethanes World Congress 1991*, Technomic: Lancaster, Pa.,100-107
19. Casagrande G. and S. Fregni (2000), "Superior Processing New all-MDI Solutions for Automotive Seating", *UTECH 2000, Conference Book of Papers*, Innovations: Automotive Developments, Paper 3.
20. Vicari C. and M. Onorato (1999), "A BE Model for the Analysis of the Effects of Seats in the Passenger Compartment Acoustic Behaviour", 1999-01-1790, *SAE Proceedings of the 1999 Noise and Vibration Conference, Traverse City, MI.*
21. Berthevas P. (1997), "Flexible Molded PU Foams are increasingly being used as the preferred solution for sound insulation in Cars, 971264, *Proceedings of the Ninth International Pacific Conference on Automotive Engineering.*
22. Klietsch J. and A. Weier (1999), 'New Low Fogging HR-surfactants Combining Environmental Concerns and added Performance', *Proceedings of the Polyurethanes EXPO'99*, Technomic: Lancaster, Pa., 95-101.

23. Mercando L.A, Kniss J.G., Tobias J.D., Plana A., Listemann M.L. and S. Wendel (1999), "Non-fugitive Catalysts for Flexible Polyurethane Foams", *Proceedings of the Polyurethanes EXPO'99,* Technomic: Lancaster, Pa., 103-134.
24. Sikorski M., Wehman C. and H. Cordelair (1999), " New Additive Solutions for Low VOC in HR Molded Foams", *Proceedings of the Polyurethanes EXPO'99*, Technomic: Lancaster, Pa., 135-143.
25. Parks K.L., Gansen P., Gricar J. R. and U. Ulman (1996), "New Developments in Polyurethane Foam systems for automotive Instrument Panels, *Proceedings of the Polyurethanes EXPO'96*, Technomic: Lancaster, Pa., 362-369
26. Larbig H., Hinz W. and P. Horn (1995), " Catalytically active Polyether Polyols", *Proceedings of the Polyurethanes Conference 1995*, Technomic: Lancaster, Pa., 212-215

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