Acoustic Absorbers: A third way for the management of sound in automobiles

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1. Abstract

The paper will first describe trends in the automotive market and then key features determining acoustic absorption of material. The paper will then highlight the development of a novel technology named ACOUSTIFLEX® from Huntsman Polyurethanes delivering acoustically "active" foams straight from production. Physical and acoustic data demonstrates that this technology is suitable for a number of application areas within the automotive market and that the balance of acoustic performance and weight outpeforms any other materials currently available on the market. The technology therefore offers producers the opportunity to enhancethe acoustic comfort of their vehicles whilst simultaneously lowering the overall weight to achieve this.

2. Introduction

Within the European automotive market there are a number of identifiable technological and economic trends that are critical when considering a proposal to supply technology to this market. In general, the factors are driving the current & future development of PUR technology can be summarised as:

- Requirement for improved "comfort" within vehicles (ergonomic & acoustic).
- Requirement for enhanced safety features & improved driving dynamics within vehicles.
- Requirement for continued reduction in cost / weight whilst providing enhanced technical effects.
- Movement towards true modularity in design and economic efficiency.
- Movement toward alternative sources of propulsion (electrical, hydrogen).
- Movement away from traditional western assembly towards eastern European based operations.[1]
- Extending service life or MTBF.[i]

Comfort is more than ever one of the major factors of car performance that can be easily characterised by the consumer to help differentiate vehicles within a similar class. It is becoming clear that within the boundary of "comfort" the acoustic performance of the vehicle is gaining in importance and the consequent production at minimum cost of safe and high quality vehicles characterised by low environmental noise and outstanding interior acoustic comfort becomes a challenging objective for the OEMs. Coupled with this target, the additional driver of constant weight reduction of the vehicles to improve fuel efficiency has become critical.

To optimise performance of vehicles by reducing vibration and noise levels whilst simultaneously reducing both the weight and the cost to manufacture the vehicle provides a significant challenge to companies who supply materials into this market. A traditional approach to manage acoustics within this environment has been the use of increasing levels of damping materials such as PUR foams or to significantly increase the wall thickness of the structure which now runs counter to the prevail trend within the automotive market.

To achieve these sometimes divergent targets required by the automotive market it is important for a materials supplier to truly understand the relationship between the chemistry, structure, morphology and physical properties of an individual technology that they supply and how it can meet the sometimes

[i] *MTBF (mean time between failure)*

divergent targets of the market. Only then can the development of relevant performance be achieved under conditions that are accepted by the automotive market.

The following paper will describe a patented PUR technology called ACOUSTIFLEX® developed by Huntsman Polyurethanes to enable the production of low weight PUR foam that is acoustically "active" when manufactured. The system is defined as "acoustically active" as it displays a very low reflection coefficient directly following manufacture without additional mechnical treatments. This has been achieved by designing technology to provide a very specific morphology resulting in exception tortuosity & porosity within the foam itself. Huntsman Polyurethanes has now developed this technology to allow the production of highly technical foams that provide the optimised balance of density range and acoustic performance (absorption) available in the market place. Foams produced with this technology can then be thermoformed into the required structure / application area and also provide the ability to construct modular systems with tuned acoustic properties.

3. Determining and delivering acoustic performance with PUR

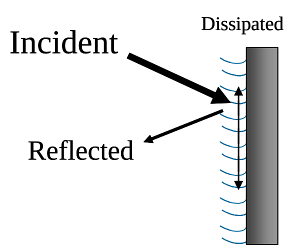
3.1. What drives acoustic activity?

The literature around the subject of sound absorption is extensive and a number of comprehensive reviews exist.[2] When developing technology to provide significant technical effects in terms of acoustic activity it is important to understand the key features of acoustic activity and how one characterises and measures such an effect.

3.1.1. Reflection coefficient

In general terms the acoustic impedance of a surface may vary with frequency, with the position on the surface and with the angle of incidence of the sound wave upon the surface (*see figure 1*).

Figure 1: Schematic of incident sound upon a surface showing critical modes of sound behaviour



The reflection coefficient of a surface is defined as the ratio of reflected sound to incident sound in the following manner.

$$RC = \frac{I_{reflected}}{I_{incident}}$$

3.1.2. Sound absorption coefficient

The reflection coefficient is hence related to the sound absorption coefficient by the following expression.[iii]

$$\alpha(f, \vartheta) = 1 - RC$$

[iii] *This accounts for absorbed AND transmitted sound.*

3.1.3. Porosity & flow resistivity

The sound absorption coefficient of a porous material (α) can then be defined in terms of a number of critical features including porosity (Φ), tortuosity (α_∞), flow resistivity (σ), thermal and viscous length.

$$\phi = \frac{V_a}{V_m}$$ *where V_m = total volume of material & V_a = voids volume within this material*

$$\alpha_\infty = \phi \frac{r_{fluid}}{r_{foam}}$$ *where r_{fluid} = resistivity of a conduction flud*

and r_{foam} resistivity of the material saturated with the conductiong fluid

$$\sigma = \frac{\Delta p}{u.\Delta x}$$ *where Δp = static pressure differential across a layer of thickness Δx and u is the velocity of flow through the material*

For the purpose of this overview the description of thermal and viscous length involves considerable mathematical complexity and is described in a number of key papers.[3]

3.1.4. Measuring acoustic performance

From these previously defined relationships is possible to determine acoustic absorption by a combination of direct methods & indirect methods. Over the past two decades significant research effort has been devoted to the development of experimental techniques dedicated to the measurement of local absorbing characteristics. Many of these involve the combination of direct and indirect methods to solve Biot's equations which govern the propagation of acoustic and elastic waves in porous media. [4]

Direct methods to determine acoustic impedance include

- *Kundt tube*[iv]
- *Alpha – cabin*[v]
- *Reverberation room*

Indirect methods:

- *Airflow measurement as function of pressure drop*
- *Direct tortuosity measurements*

More recently, advances in computing power and sophistication have enabled the development of algorithms that works with output data from impedance tubes calculating the "geometric parameters" viscous and thermal characteristic length and tortuosity. These systems will also enable the characterisation of flow resistivity and porosity in a relatively simple manner.

3.2. What features are critical to the optimisation of absorption performance for a polyurethane

From the description of the key features impacting the sound absorption coefficient it is clear that a number of features of basic polyurethane foam technology will significantly impact the absorption performance.

[iv] *Plain wave absorption.*
[v] *Diffuse absorption.*

These features can also be categorised as being part of the intrinsic material properties (or how the material is formulated) or being defined as part or consequence of the conditions under which the system is processed:

Material properties:

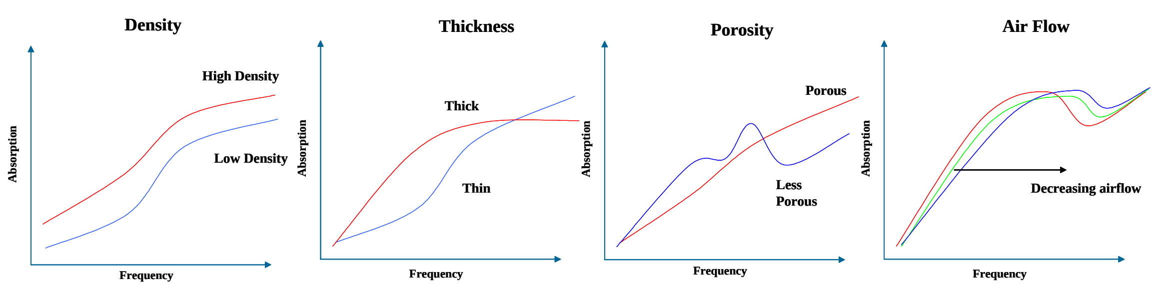
- *Density*
- *Porosity*
- *Tortuosity*

System properties:

- *Total thickness and surface*
- *Presence of membrane*
- *Presence of Layers, incl. "skin"*

The impact of these features on the performance of a foam system to absorb sound can be described in a simple schematic manner noting that in reality it is actually impossible to separate the impact of effects as they are linked. If it were possible to change key variables whilst holding other variables constant the following relationships could be established (*see figure 2*).

Figure 2: Schematics of the key features driving absorption performance



Summarising the effects highlighted in the graphs increasing density / thickness / porosity and airflow[vi] will result in increased levels of absorption performance and with that the potential to improve the acoustic comfort of any space that these materials are used within.

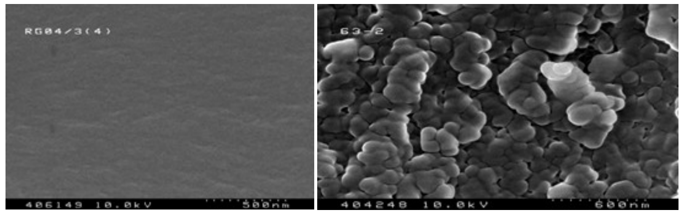
3.3. How does foam morphology lead to acoustic performance

Based on the assessment of the key features that drive absorptive performance when considering how to deliver optimum performance it is clear that both increasing density & thickness of any foam system are obvious solutions to increase performance. However, when considering the basic requirements of the automotive industry both these required features run counter to the prevailing trend within the automotive market.[5] Therefore, any technology that can meet these requirements must have the intrinsic and novel chemistry & morphology to deliver exceptional porosity & air flow values. Over the past years within Huntsman we have spent considerable resource in developing a patented foam technology that provides very high porosity and air flow directly post-manufacturing without any form of additional treatment.

To highlight what impact this novel chemistry has the following images show the significant difference in the structure of the new foam technology versus traditional rigid foam directly following processing (*see figure 3*).

[vi] *The impact of these variables needs to be understood as does the magnitude of potential increase.*

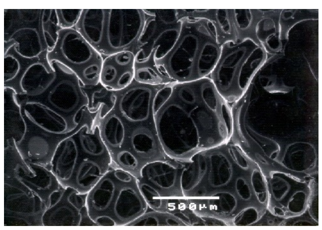
Figure 3: Comparison of conventional polyurethane rigid foam with ACOUSTIFLEX® acoustic absorber



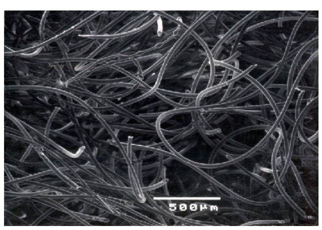
Conventional PU Rigid Foam ACOUSTIFLEX® acoustic absorber

In is also interesting to directly contrast the morphology of this foam technology versus both typical flexible polyurethane foam and traditional fibre materials (*see figure 4*). From the images it is clear that the novel foam technology corresponds more closely to the morphology of a fibre product but it is important to note the significant difference in the average density of the materials. It appears simplistically that the new ACOUSTIFLEX® foam technology delivers the same structural characteristics that drive high levels of absorption but at significant density reduction when compared to traditional fibre based technology.

Figure 4: Images of the morpholical structure of conventional PUR foam, fibres and ACOUSTIFLEX® *foam*



Conventional Flexible Foam @ Density 40 kg/m^3



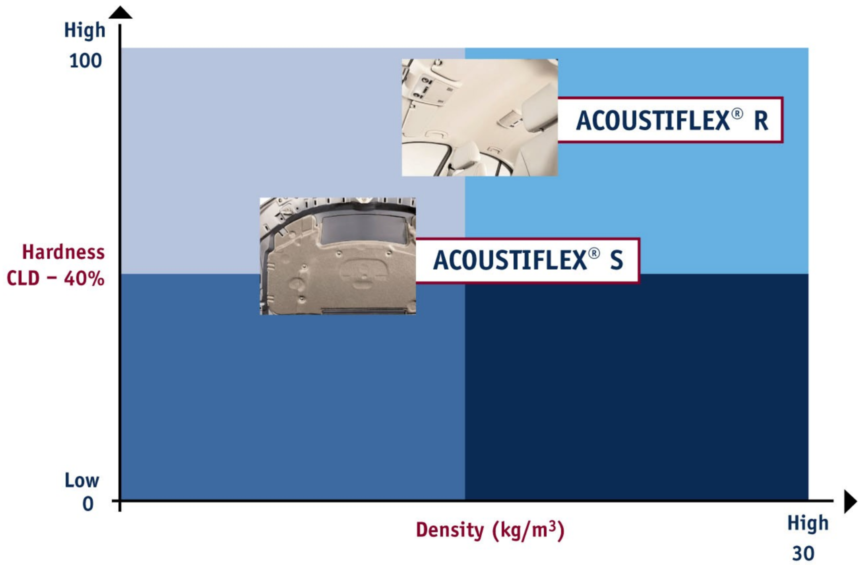
Fibre Technology @ Density 35 kg/m^3

ACOUSTIFLEX® S @ Density 15 kg/m^3

3.4. ACOUSTIFLEX® Technologies

Over the past years the technology basis has been extended to deliver a rnage of materials described as a series of ACOUSTIFLEX® products. By tuning the chemistry available it is possible to deliver materials with a broad range of physical effects whilst still delivering excellent acoustic performance. The positioning of the various ACOUSTIFLEX® technologies can be simply defined using the following scheme (*see figure 5*).

Figure 5: Schematic of potential product characteristics within the ACOUSTIFLEX® Platform



3.3.1. ACOUSTIFLEX® R

Initial targets for the technology have been application areas that rely on relatively stiff / rigid physical characteristic and therefore the material is direct placed opposite traditional rigid type PU foam composites and various fibre & glass matt type composites.[6] Application areas that require this balance of properties include automotive headliners.

3.3.2. ACOUSTIFLEX® S

The technology has also been extended to provide a different balance of physical / acoustic performance maximising the absorption of the frequencies generally associated with engine noise, whilst meeting additional requirements of flame retardency and thermal resistance. This has enabled the use of the technology within the engine compartment.

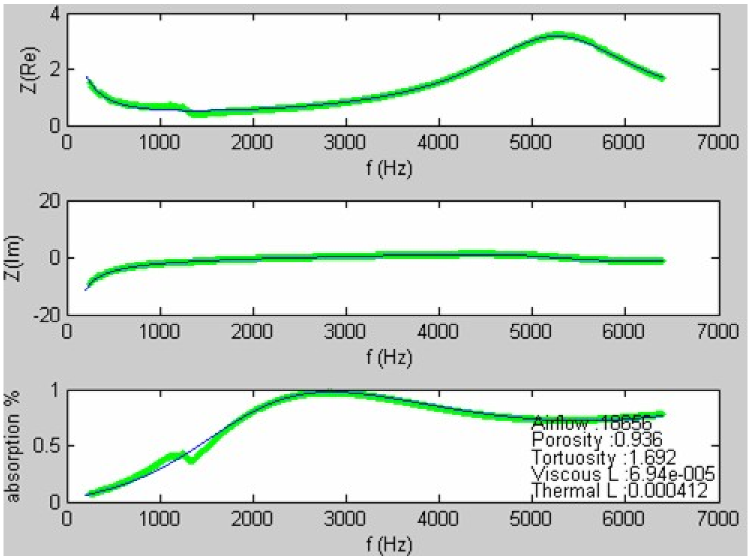
4. Characterisation of performance of ACOUSTIFLEX® type systems

A formulation was developed for this study to enable an indicative type of performance to be characterised. Foams were produced under as near identical conditions in terms of index and other factors as possible. Blocks were produced using a simple batch block production machine.For each block the materials were cast at room temperature. Demolding time was approx 5 to 10 minutes. After moulding the blocks were allowed to cure for a further 24hrs and then cut into appropriate sizes for further processing. Prior to testing the foam samples were conditioned for 48hrs at 25 deg C and 50% relative humidity.

4.1. Comparative test results: Acoustic properties of ACOUSTIFLEX®

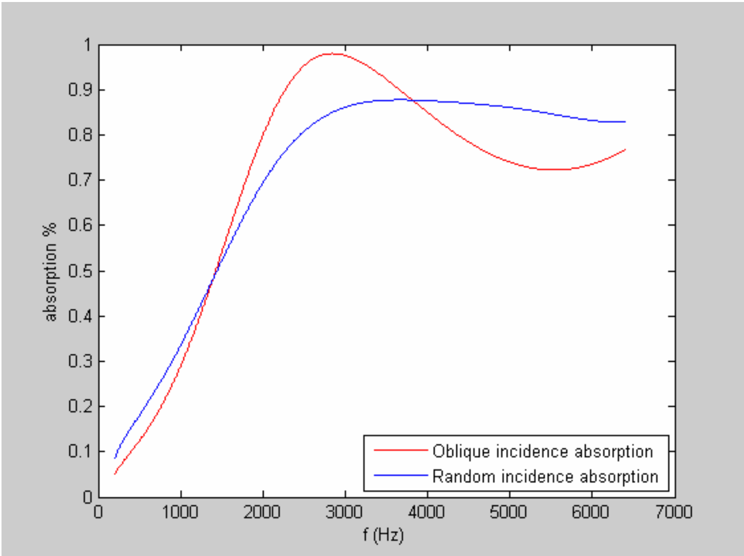
Measurement of the foam samples produced under standard processing conditions with a Kundt tube and associated software allows the determination of the Biot parameters for a given system. An example output is given below (*see figure 5*).

Figure 5: Schematic of curve fitting to determine Biot parameters for ACOUSTIFLEX® R Platform



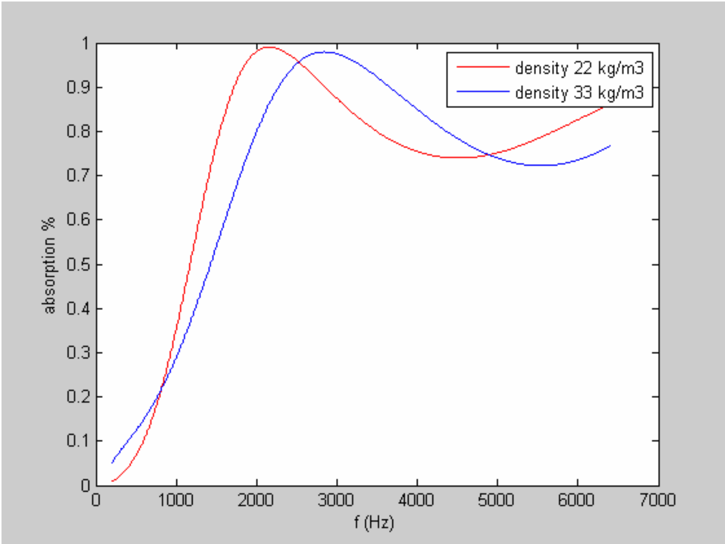
Using these values it is then possible to determine the impact of various factors on the performance of the foam systems. In addition to the impact of physical characteristics it is also possible to model the impact of various types of measurement conditions on the performance of the system. The example shown below highlights the difference between oblique & random incidence (*see figure 6*).

Figure 6: Impact of measurement type on absorption behaviour of an ACOUSTIFLEX® R system calculated following the determination of Biot parameters



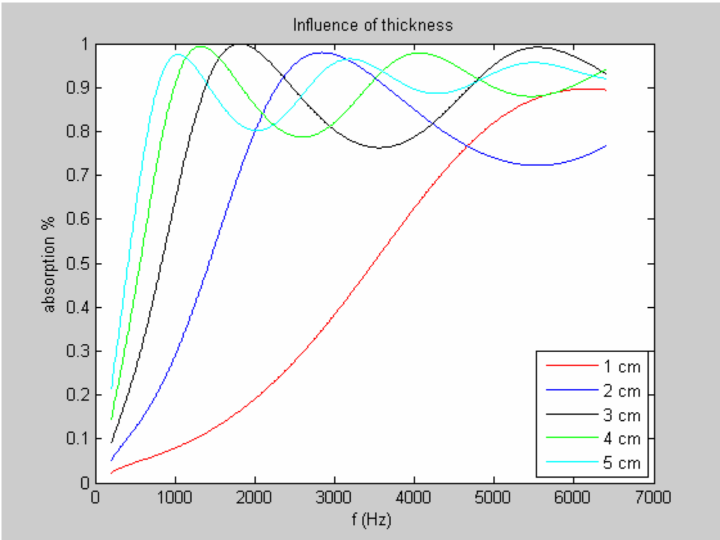
Using the determined Biot parameters it is then possible to investigate the impact of various processing / formulation changes on the system. The first example shown below is that of increasing the density of the ACOUSTIFLEX® R foam system from22kg/m^3 to 33kg/m^3 (*see figure 7*).

Figure 7: Impact of foam density on absorption behaviour of an ACOUSTIFLEX® R system calculated following the determination of Biot parameters



The following shows the impact of foam thickness at a constant density on the measured absorption behaviour of the ACOUSTIFLEX® R system. The curves were again computed following the determination of the relevant Biot parameters (*see figure 8*).

Figure 8: Impact of foam thickness on absorption behaviour of an ACOUSTIFLEX® R system calculated following the determination of Biot parameters



4.2. Comparative test results: Physical Properties

In addition to the acoustic properties of the ACOUSTIFLEX® systems the following tables highlight typical physical properties for the resultant foams as characterised using standard test methodologies. The data listed below show the typical required density ranges for the ACOUSTIFLEX® R and ACOUSTIFLEX® S technologies within the individual application areas (*see Tables 1 & 2*).

4.2.1. ACOUSTIFLEX® R acoustic absorbers

Table 1: Comparative physical property data for stiff acoustic absorber technology

Physical Property	**Unit**	**Method**			
Density	kg/m^3		23	28	33
Compression Hardness	kPa	ISO844	70-80	90	100
Stiffness	N/m	SAEJ949	6	8	11
Tensile Strength	kPa	ISO1798	140	155	180
Elongation	%	ISO1798	14-18	17-20	24-28
Fogging	%	DIN75201	92	92	92
Fogging	mg	DIN75201	0.7	0.7	0.7
FMVSS 302	mm/min	FMVSS302	72-80	<70	<70

4.2.2. ACOUSTIFLEX® S Acoustic absorbers

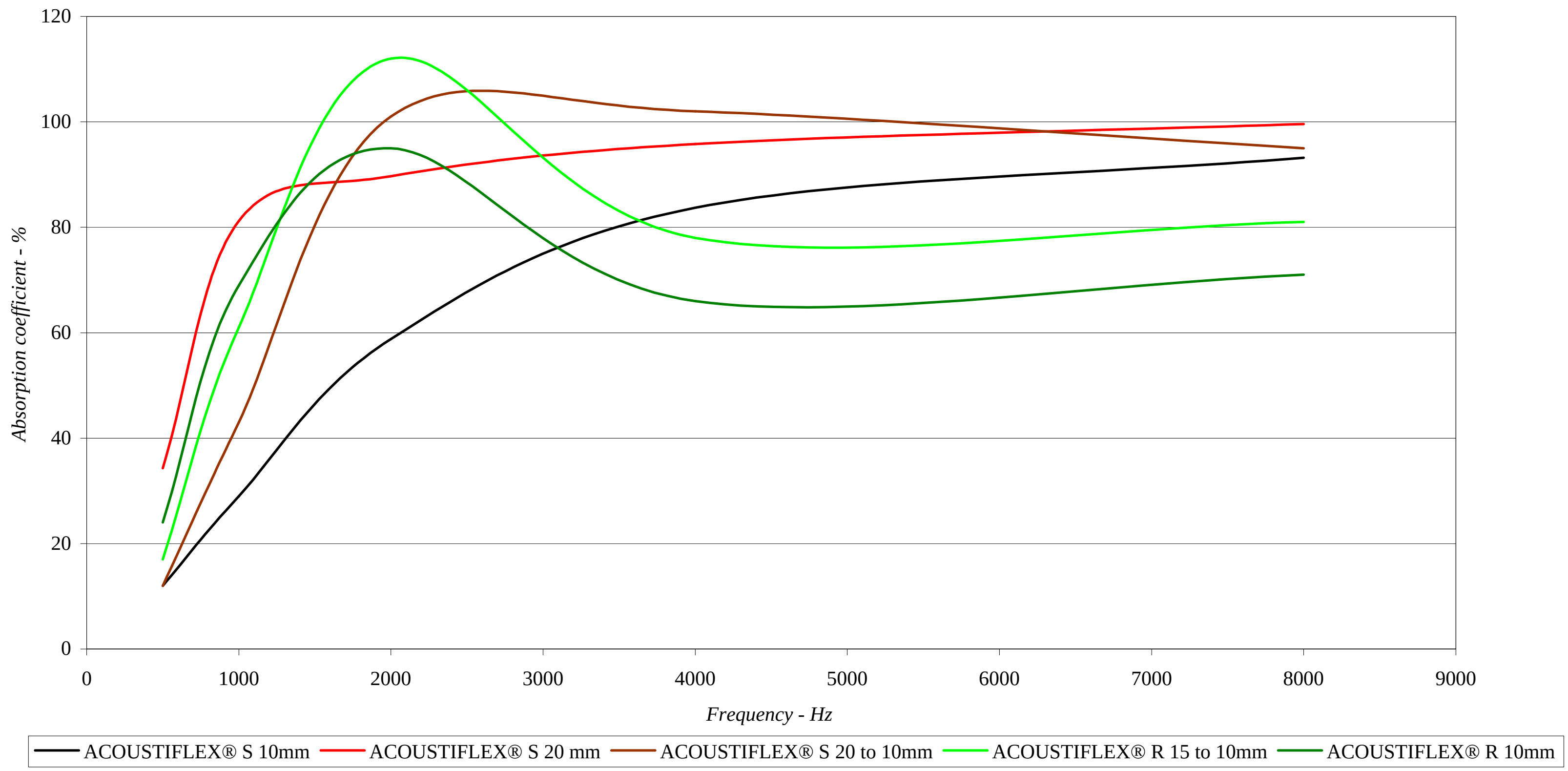
Table 2: Comparative physical property data for stiff acoustic absorber technology

Physical Property	**Unit**	**Method**		
Density	kg/m^3		17	19
CLD 40%	kPa	ISO3386/1	25	32
Tensile	kPa	SAEJ949	60	70
Elongation	%	ISO1798	17	19
Fogging	%	DIN75201	86	86
Fogging	mg	DIN75201	0.8	0.8
FMVSS 302	mm/min	FMVSS302	72	80

4.3.2. Comparative test results: Acoustic Properties

In addition to the determination of the absorption characteristics of the ACOUSTIFLEX® systems using Kundt tube / determination of Biot parameters the following figure highlights the direct measurement of the aborption behaviour of the materials using an alpha cabinet. For each sample a representative foam sample was produced, conditioned and then placed within the cabinet. The report performance of the materials is in Sabine absorption coefficients (*see figure 9*).

Figure 9: Plot of measured alpha cabinet data for a number of the ACOUSTIFLEX® technologies measured on foam samples[vii]



[vii] *Sabine Absorption coefficient*

5. Conclusions

- The delivery of improved acoustic comfort within the automotive market whilst at the same time reducing weight is becoming an increasingly important driver.

- Using a novel foam technology Huntsman Polyurethanes is able to deliver a technical foam product with high tortuosity and airflow values coupled with outstanding physical properties at low densities. The foams carry the trademark ACOUSTIFLEX®.

- Development of characterisation methodologies to measure and characterise the impact of composite design within the ACOUSTIFLEX® technologies enables the construction of materials to meet a broad range of application requirements.

- Testing the ACOUSTIFLEX® system versus standard PU foam technology by Kundt tube / Biot parameter or alpha cabinet shows the dramatic improvement in acoustic performance.

- The ACOUSTIFLEX® R & ACOUSTIFLEX® S technology currently enables the production of foams to meet technical requirements within the headliner & under bonnet application area in the automotive market.

- When compared on a total performance basis (physical properties / acoustic performance / weight) the ACOUSTIFLEX® systems are clearly superior to traditional fibre technologies and offer significant possibilities for innovation within the automotive market.

6. Glossary

Absorption coefficient: The sound absorption coefficient defines the fraction of sound energy absorbed by, for example, one reflection from a wall. Energy is proportional to the square of sound pressure, so for an absorption coefficient of 0.2, 20% percent of the energy is absorbed, reducing the sound pressure by 10.6%.

Amine: A class of compounds used as catalysts in polyurethane foam reactions. Amines are characterized by having N, NH or NH_2 groups in the molecule.

Air-borne noise: This refers to noise which is fundamentally transmitted by way of the air and can be attenuated by the use of barriers and walls placed physically between the noise and receiver.

Catalyst: A substance that changes the rate of a chemical reaction.

Cell Opener: A compound added to a foam formulation for the specific purpose of increasing the population of open cells. Successful cell opening is evidenced by higher airflow and decreased foam shrinkage.

Chain extender: Short-chain reactive molecules joining diisocyanates in a linear fashion to form crystalline hard segments that modify the properties of a polyurethane.

Demold time: The time between the discharge of the foam ingredients from the mixing head and the time at which a molded object may be removed readily from the mold without tearing or altering its shape and without post-expansion.

Density: Density is the weight per unit volume of the foam normally expressed in kilograms per cubic meter (kg/m^3). The general range of polyurethane foams is 12 to 90 kg/m^3.

System: A chemical system for producing foam which consists of only two materials. One part is referred to as the isocyanate side and is usually the 'pure' isocyanate with no additives. The second part is often called the resin side and usually consists of blended polyol(s), catalysts, surfactants and other desired additives.

Low-frequency noise: Containing major components within the low frequency range (20Hz - 250Hz) of the frequency spectrum.

MDI: The basic monomer of a di-functional isocyanate

OEM: Original Equipment Manufacturer. A term used to describe automotive producers such as BMW, Ford, Renault.

Polyol: Generally, any organic molecule containing a plurality of hydroxyl groups. For polyurethane foams, polyols are usually polyethers (or formerly polyesters) with hydroxyl reaction sites.

Sabine: A unit of measure for sound absorption. 1 = the absorption of one square foot of a surface having 100% absorption e.g. an open window).

Silicones: Chemicals formed from a combination of silicon and organic molecules that exhibit surface-active properties. These compounds are used to add stability to

	the liquid foaming mixture so that drainage is retarded and flowability of the mass is improved.
Sound:	A fluctuation of air pressure which is propagated as a wave through air.
Sound absorption:	The ability of a material to absorb sound energy through its conversion into thermal energy.
Suprasec:	Registered trade name for isocyanate systems marketed by Huntsman Polyurethanes

Biographies

Chris Skinner

Chris Skinner holds a Ph.D. in organofluorine chemistry and an M.B.A. He join ICI in 1995 and has worked in a number of technology areas including KLEA, Tioxide Specialties, Composite Wood product, Thermoplastic polyurethanes and more recently Automotive. He has held a number of positions in technical and marketing areas and is currently the Automotive Platform manager based in Brussels. Chris Skinner has published numerous articles and currently holds 14 patents.

Jan Vandenbroeck

Jan Vandenbroeck joined ICI in 1980 and has worked on fundamental research aspects and development of Polyurethanes in many areas including Rigids, Material characterization, Polymer science, FEA, technical computing, mathematical and statistical modeling. He is a PU expert in product modeling based in Brussels. He holds an MSc in scientific computer technology and academic degrees in chemistry, electronics and software engineering.

Johan Peters

Johan Peters holds a Bachelors degree in process chemistry. He joined ICI in Belgium in 1992. Since joining he has held a number of development positions and has been involved in many development projects with Tier 1 & Tier 2 suppliers of acoustic components & systems for the global automotive industry. Johan Peters currently holds the position of Automotive Product Manager (Acoustics) within the European automotive SMU.

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