

RECYCLABILITY OF POLYURETHANE FROM END-OF-LIFE VEHICLES

Status Report

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September 2026

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1. Abstract

This status report examines the **recyclability** of polyurethane (PU) foam recovered from **end-of-life vehicles (ELVs)** in the context of the [European Union Regulation 2026/1738](#) introducing higher **recycled-plastic-content requirements** and **recycling targets** for plastics. The study demonstrates the technical feasibility of both **mechanical** and **chemical recycling** of PU foam from ELVs. **Mechanical recycling** into sports mats was successfully demonstrated, whereas **chemical depolymerisation** of PU into recycled polyols remains constrained by **feedstock-purity requirements**. The study also investigates **hydrothermal carbonisation (HTC)** as a potential route for processing unsorted automotive shredder residue (ASR) without extensive pre-cleaning. Overall, the report provides a technical overview of the **principal barriers** and **emerging solutions** relevant to achieving **circularity targets** in the automotive supply chain.

2. Background

The European Union has reached a final agreement on the provisions of a new **End-of-Life Vehicles (ELV) Regulation** ¹⁾, representing a significant transition from the previous Directives to a unified and directly applicable legal framework. The Regulation is intended to support the transition towards a circular economy in the automotive sector by introducing **stringent requirements throughout the entire vehicle lifecycle**. Unlike a Directive, which requires transposition into national law, a Regulation is **directly applicable in all Member States**. This provides a **harmonised legal framework** across the EU and reduces national differences in the **management of automotive waste and vehicle-design requirements**. The most significant change is that the Regulation no longer focuses solely on the treatment of vehicles once they are scrapped. Instead, it **addresses the entire vehicle lifecycle**, from **design and production** through **reuse and recycling** to **final treatment** at end of life.

Key provisions include:

- **Mandatory Recycled Content Targets**

New type-approved vehicles in categories N1 and M1 must meet a recycled plastic content target of **15% by 2032**, increasing to **25% by 2036**. In addition, **20% of the recycled plastic target** must be met using **closed-loop sources**, such as materials recovered from ELVs or parts removed during the vehicle use phase.

- **Specific inclusion of polyurethane**

Although most thermosets are excluded from these targets, **PU foams used for cushioning** are explicitly **included in the recycled-content requirements**.

- **30% recycling target for plastics recovered from end-of-life vehicles**

The **30% recycling target** is a complementary requirement introduced by the new End-of-Life Vehicles Regulation and specifically concerns the **treatment of plastic waste** once a vehicle reaches the end of its life. This 30% treatment target should be distinguished from the recycled-content targets applicable to vehicle manufacturing.

- The **30% target** refers to the **proportion of plastic recovered** from a scrapped vehicle that must be recycled.
- The **15% and 25% targets**, respectively, refer to the **proportion of recycled plastic that must be incorporated** into a new vehicle, **in addition to the 20%** closed-loop requirement (the “recycled-content targets”).

- **Stronger Extended Producer Responsibility (EPR)**

The Regulation significantly strengthens **Extended Producer Responsibility (EPR)**. **Manufacturers will be responsible** for the treatment of their **vehicles at end of life**. This includes **free take-back of ELVs from the last owner** and **cross-border EPR obligations** even where a vehicle reaches end of life in another EU country. Manufacturers will also be required to provide more detailed information on the **materials used in a vehicle**, the **location of components**, **safe dismantling procedures**, and **recycling and reuse options**. The strengthened EPR framework also includes **more stringent design-for-recycling** requirements.

- **Rules on used vehicles versus ELVs**

A major issue today is that many vehicles disappear from EU records. The new rules are intended to **reduce illegal exports of scrap vehicles** presented as used cars, **unregulated dismantling**, and **environmental pollution** resulting from improper disposal.

- **Timing**

The text of the Regulation was provisionally agreed between the Council of the European Union and the European Parliament in **December 2025**. **Formal adoption** is still required and is expected to take place in the **second half of 2026**.

It is estimated that a passenger car contains **24–28 kg of PU**, most of which is **flexible PU foam**. The largest share is used as **cushioning in seats (8–10 kg)**, while the remainder is distributed across numerous smaller components. When assessing the potential for recycling PU from ELVs, it is therefore appropriate to **focus on car seats**. Nearly **11 million passenger cars** were produced in the **EU in 2025** ²⁾. This corresponds to approximately **90–110 kt of PU foam in seats** and a **total PU content** of approximately **260–310 kt**. These figures **do not include commercial vehicles**.

3. Project Description

Little research, however, was carried out on the possibility of **removing PU from ELV seats before shredding**. Early concepts on reverse logistic from end-of-life vehicles (ELVs) is frequently cited and discussed in academic literature³⁾ and in publications of the Dutch ARN system (Auto Recycling Nederland) to create a coordinated **closed-loop system** for ELVs.

Very little publicly available information exists on the **specific purity requirements** for polyurethane foam recovered from end-of-life vehicles for either mechanical or chemical recycling. In addition, preliminary investigations are needed to determine whether **unsorted, PU-containing Automotive Shredder Residue (ASR)** is suitable for **thermochemical recycling**.

The project evaluated both **post-industrial and post-consumer PU foam**. The collected ELV PU foam was divided into **two representative fractions** for **chemical and mechanical recycling**. For **chemical recycling**, the study focused on determining the proportion of **conventional polyol** that could be replaced by **recycled polyol** without compromising OEM specifications. For **thermochemical recycling**, initial investigations were conducted to assess whether **HTC technology** could also be used for the **pre-treatment of Automotive Shredder Residue (ASR)**.

The envisaged project was structured as a **collaborative initiative across the supply chain**, with the objective of improving understanding of the challenges associated with recycling PU from ELVs. Based on the knowledge generated, the project also aimed to formulate **recommendations on measures that could facilitate improved recycling of PU from ELVs in the future**.

4. Obtaining ELV – Foam

4.1. Issues with collection/dismantling/shredding/contamination

Following **deregistration**, ELVs are generally **drained of technical fluids** such as engine oil, brake fluid and air-conditioning coolant. **Plastic components** such as bumpers are removed before the vehicle is fed into a shredder. In vehicle-shredding systems, the shredded material is typically subjected to **air separation before metal separation**. This produces a light, airborne fraction known as **shredder light fraction (SLF)** and a **shredder heavy fraction (SHF)**, which contains, among other materials, metals. SLF is a highly complex mixture containing plastics, films, fibres and other materials. A substantial proportion of SLF consists of **PU foam contaminated** with residual oil, metal dust generated during shredding⁴⁾, and other plastics.

In addition, ELVs are commonly stored **outdoors** and **exposed to weather conditions**, which can result in wet vehicle interiors and, consequently, **wet PU foam in the seats**. This considerably **reduces the number of ELVs** from which foam suitable for chemical or mechanical recycling can be recovered. Current chemical and mechanical recycling processes require **clean, dry ELV PU foam**. **Cross-contamination** with other plastics, fibres or operating fluids is prohibitive and can result in **significant losses of collected ELV foam** because of the additional cleaning steps required. Consequently, according to the current state of technology, **SLF cannot be used directly for depolymerisation or mechanical recycling**.

4.2. Description of work performed

Dismantlers and recyclers were contacted to identify methods for collecting PU foam from ELVs in a condition suitable for recycling. Feedback from most operators indicated that **manual removal of PU foam** from car seats is the **most effective method** for obtaining the required foam quality. However, manual dismantling of car seats is **highly time-consuming** and is **not a standard procedure among dismantlers or recyclers**.

Nevertheless, it was decided to obtain both **manually dismantled and machine-assisted dismantled** PU foam from ELVs. Contracts were concluded with two dismantlers, **LSH Lübecker Schrotthandel GmbH** and **Herfel Entsorgung GmbH**, to supply clean and dry ELV PU foam. In total, approximately **50 ELVs were dismantled**, yielding approximately **600 kg of clean ELV PU foam**. The recovered foam components were subsequently **shredded into flakes** by **Federal Eco Foam** (Lommel, Belgium) and used in **mechanical and chemical recycling trials**.

4.3. Share of TDI- and MDI-based foams and methods for identification

Different types of PU foam are commonly used in automotive applications. **Front seats** are frequently manufactured using **MDI-based foam**, whereas **rear seats** are often made from **TDI-based foam**. Because TDI- and MDI-based foams are produced from different raw materials, the **recycled polyols** obtained from them may have **different properties**. This may affect the range of **PU formulations** in which the resulting recycled polyols can be used. Several analytical approaches were therefore evaluated to identify the **different PU foam types**.

4.3.1. Sorting PU foam using production data from PU foam suppliers

The initial approach was to **trace the foam type** used in dismantled car seats using the **ELV vehicle identification number** and **foam-producer databases**. This approach proved **unsuccessful** because the available databases maintained by foam producers generally cover **no more than ten years**, whereas the ELVs collected for the project were substantially older.

4.3.2. Sorting PU foam using near-infrared detection

Analyticon Instruments GmbH was contacted regarding a handheld device based on **near-infrared (NIR) technology** for the rapid identification of different plastic types. To extend the capabilities of the equipment, the company proposed testing whether the device could also differentiate between different types of PU foam.

A first-round feasibility evaluation was conducted at **Adient** in Strasbourg using **laboratory foam samples**. Several PU foam samples were tested, and the NIR equipment appeared to **differentiate reasonably well** between certain foam types. The NIR detector was calibrated using the **IR spectra of the laboratory samples** supplied.

Post-industrial foam: MDI components were tested at least **two hours after production**, once the parts had cooled. The NIR device **correctly identified MDI-foam**. TDI components were also tested at least two hours after production. For these samples, the NIR device alternately identified MDI or TDI foam depending on the point of contact with the foam surface. **Reliable identification of TDI** technology was therefore not possible. To assess the possible influence of release agents on the measurements, **core foam was also analysed**; however, this did not improve the results.

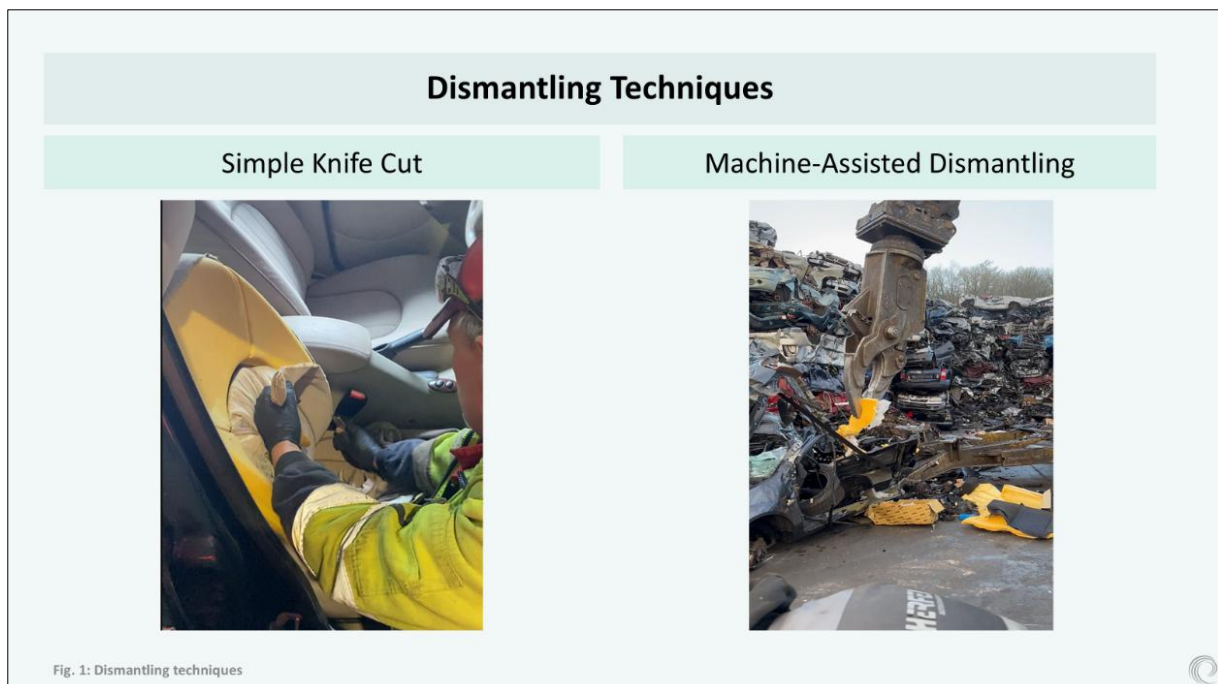
Post-consumer foam: In view of the inconclusive results obtained with post-industrial foam, **post-consumer foam was not tested**.

In summary, Analyticon Instruments GmbH indicated that it would assess possible next steps internally and might subsequently revert to the project team. Alternative devices are available from **Redwave®**, an Austrian company specialising in **recycling and waste-treatment solutions**.

Ultimately, the project team decided **not to pursue technologies for differentiating PU foam types** at this stage, as sorting ELV foam by PU type would add excessive complexity to the ELV PU foam recycling process.

4.3.3. Dismantling techniques for recovering PU foam

To obtain clean and dry ELV PU foam, the contracted recyclers stored selected ELVs in a **recycling depot** after deregistration. Two techniques were used to **recover PU foam** from car seats: **manual cutting with a knife** and **machine-assisted dismantling** (Fig. 1).



Simple knife cutting: After removal of the textile covering, the PU foam was **cut out of the seat**. The principal advantage of this technique is that, provided the operator follows clear instructions on foam cleaning, the recovered foam can be **used without additional cleaning treatment**.

Machine-assisted dismantling: Machine-assisted dismantling was performed using specialised equipment. An excavator fitted with a dedicated grab was used to extract PU foam from the car seats. This method was substantially **faster than manual dismantling**, but **post-cleaning was required** to remove other plastics, cables and airbag detectors (**Fig. 2**).

Machine-Assisted Dismantling



Fig. 2: Machine-Assisted Dismantling



4.3.4. Discussion on how this could be improved

- **Appropriate storage of ELVs** before dismantling is a prerequisite, for example in a recycling depot, to **prevent exposure to outdoor weather conditions**. However, recycling depots that enable clean and dry storage of ELVs before dismantling are **not yet common across EU Member States**.
- Additional **research and development** are required to **improve dismantling efficiency without compromising the quality of ELV foam** intended for chemical and mechanical recycling. The PU industry is addressing this challenge; for example, **Dow and Gruppo Fiori** ⁵⁾ are cooperating on the development of an **automated recycling process** for recovering PU foam from ELVs.
- **Design for dismantling** could include **modular car-seat** concepts to accelerate the dismantling process.
- In addition, a **mono-material approach**, for example a car seat made exclusively from PU materials (PU foam cushions combined with a PU textile or leather covering), could help address the long-standing challenges associated with the multi-material construction of car seats.

5. Mechanical Recycling

5.1. Description

In **mechanical PU recycling**, PU foam is **crushed or granulated into smaller particles**. These polyurethane residues are subsequently combined using binders or fresh PU material and **consolidated under heat and pressure** to form a new composite material. The resulting moulded products can contain approximately **80–90% recycled material**. Both rigid and flexible PU foams can be processed in this manner. The recycled composite material can be used in a range of applications, including **carpet underlay, soundproofing products and sports mats**.

5.2. Test at Federal Eco Foam

A block of rebounded PU foam was manufactured at **Federal Eco Foam** (FEF, Belgium) using cleaned ELV foam flakes. The recovered PU foam components were **shredded** at FEF to ensure that the flake size was compatible with the company's standard production process. The ELV foam flakes were then **bonded to form a rebounded foam block (Fig. 3)**. The block was subsequently **cut into sheets**, and the surfaces were **covered with vinyl and anti-slip layers** to produce sports mats.



According to FEF, **processing ELV foam flakes** was comparable to **processing standard foam flakes**.

Emission testing of the ELV PU flakes was conducted at Centexbel (Belgium) (Analysis report: 25.05415.00, date 26-11-2025) in accordance with **CertiPUR™ legacy substance test**. Overall, **no issues** relating to legacy substances were identified. The results for the individual substances indicated that the sample **did not contain substances on the REACH candidate list of Substances of Very High Concern (SVHC)** at concentrations above 0.1 wt.-%. Overall, the testing results demonstrate that the **ELV PU foam flakes can be used for mechanical recycling**.

6. Chemical Recycling

6.1. Depolymerisation

In addition to mechanical recycling, PU can be recycled **chemically** using several processes, including **acidolysis** and **glycolysis**. These processes generally involve **elevated temperatures**, under which **polyurethane chains are broken down** into **precursors of the original raw materials** through **depolymerisation**. The resulting **recycled polyols** (r-polyols) are often **brown to dark brown** and may exhibit **properties and functionalities similar** to those of the original polyols. They can therefore potentially be used to manufacture products similar to those from which they were recovered. However, the **proportion of virgin polyol** that can be replaced by r-polyol **is limited**, and **adjustments to the PU formulation** are required to achieve performance comparable to that of formulations based entirely on virgin polyol.

6.1.1. Post-industrial foam

Background

Before ELV PU foam was tested, **post-industrial foam** was used to investigate the effects of **cross-contamination with other plastics** typically present in automotive seats, as well as the effects of different MDI/TDI foam ratios on r-polyol quality and performance. The post-industrial PU foam was supplied by **Adient**, which also conducted initial screening trials to determine an appropriate replacement ratio of r-polyol to virgin polyol.

Post-industrial foam - conversion into r-polyols

Post-industrial PU foams, comprising automotive-seating HR-MDI foam, HR-TDI foam and 50/50 mixtures of the two, were **converted into r-polyols** using H&S Anlagentechnik GmbH process technology. In addition, PU foams were **deliberately contaminated** with **POM, EPP and PES fleece** to investigate the effect of plastic cross-contamination on the recycling process.

Fig. 4 summarises the r-polyols produced and the effects of the plastic contaminants on the process.

R-Polyol (Sample ID)	Foam type	HR-MDI foam	HR-TDI foam	Added contaminants	Comments
WSA 550	post-industrial	100%	-	-	No abnormalities
WSA 551-2	post-industrial	-	100%	-	No abnormalities
WSA 553	post-industrial	50%	50%	-	- No abnormalities. - Foam could be dissolved. - No filtrate.
WSA 573	post-industrial	50%	50%	10% POM	- No abnormalities. - Foam and contaminants could be dissolved. - No filtrate.
WSA 577	post-industrial	50%	50%	10% EPP	- No abnormalities, beside insoluble contaminant. Foam could be dissolved. - Filtration exceedingly complex due to contaminant clogging the filter. - Not feasible at industrial scale.
WSA 580	post-industrial	50%	50%	10% PES fleece	- No abnormalities beside insoluble contaminant and agitation blockage appeared during the reaction. - The foam could be dissolved. - Filtration impossible.

Fig. 4: Converting Post-industrial PU foam into R-Polyols

The results presented in **Fig. 4** demonstrate that **MDI- and TDI-based foams**, as well as mixtures of the two, can be **chemically converted into r-polyol precursors**. However, **plastic contaminants** such as EPP and PES fleece **adversely affect the process** and should therefore be **minimised** or **removed** before chemical recycling.

Fig. 5 summarises the **physical properties** of the r-polyols produced. The r-polyols were subsequently subjected to **PU foam performance testing**. R-polyols **WSA 577** and **WSA 580** were not tested because the added contaminants caused significant manufacturing difficulties.

R-Polyol (Sample ID)	Foam type	HR-MDI foam	HR-TDI foam	Added contaminants	Hydroxyl number [mg KOH/g]	Acid number [mg KOH/g]	Amine number [mg KOH/g]	Viscosity [mPa*s] at 25°C
WSA 550	post-industrial	100%	-	-	27 ± 2	4,2 ± 0,5	9,45 ± 1	6.300 ± 500
WSA 551-2	post-industrial	-	100%	-	36 ± 2	1,4 ± 0,5	9,6 ± 1	10.300 ± 500
WSA 553	post-industrial	50%	50%	-	36 ± 2	1,4 ± 0,5	7,3 ± 1	11.600 ± 500
WSA 573	post-industrial	50%	50%	10% POM	21	1,8	13,1	10.200
WSA 577	post-industrial	50%	50%	10% EPP	28	1,4	6,8	9.800
WSA 580	post-industrial	50%	50%	10% PES fleece	25	1,4	5,8	6.000

Fig. 5: Properties of R-Polyols

Performance tests

Performance tests were conducted by **replacing 50% of the standard polyol** with r-polyol in all-MDI and all-TDI automotive-seat PU formulations, respectively (**Fig. 6**). Because the r-polyols themselves contained approximately 50% recycled material, the calculated **closed-loop recycled content** of the final PU foam was **15% for the MDI formulation** and **19% for the TDI formulation**.

MDI Control Formulation			TDI Control Formulation		
General Seating Formulation	Formulation	Formulation	General Seating Formulation	Formulation	Formulation
Polyol	100,00	50,00	Polyol A	70,00	16,00
r-polyol, 50% recycled content	-	50,00	r-polyol, 50% recycled content	-	54,00
Cell opener	1,30	1,30	Polyol B, SAN-polyol	30,00	30,00
Water, added	3,50	3,50	Water, added	2,90	2,90
DEOA, 100 %	0,60	0,60	Glycerol	0,60	0,60
DABCO® NE300	0,20	0,20	DEOA LF	0,94	0,94
DABCO® NE1082	0,90	0,90	TEGOSTAB® B8761 LF2	0,70	0,70
Tegostab® B8734 LF2	0,80	0,80	DABCO® NE1090	0,95	0,95
Summe Premix	107,30	107,30	DABCO® NE300	0,12	0,12
			DABCO® BA306	0,50	0,50
MDI	60,25	60,25	Summe Premix	106,71	106,71
			TDI	37,33	37,33
Total	167,55	167,55	Total	144,04	144,04
Index	100,00	100,00	Index	100	100
Recycled content	-	15%	Recycled content	-	19%

Fig. 6: Test formulations

The following performance parameters were evaluated: **reaction kinetics** (rise profiles), **physical foam properties**, **emissions according to VDA 278**, and **aldehyde emissions** (Figs. 7–9).

H&S Anlagentechnik - Recycled Polyol WSA 550

Lab Sample #	Foam type	MDI	TDI	Added contaminants	Hydroxyl number [mg KOH/g]	Acid number [mg KOH/g]	Amine number [mg KOH/g]	Viscosity [mPa*s] at 25 °C	Comment
WSA 550	Post – Industrial	100%	-	-	27 ± 2	4,2 ± 0,5	9,45 ± 1	6.300 ± 500	Tested with 50% virgin polyol replacement No specific process issue detected

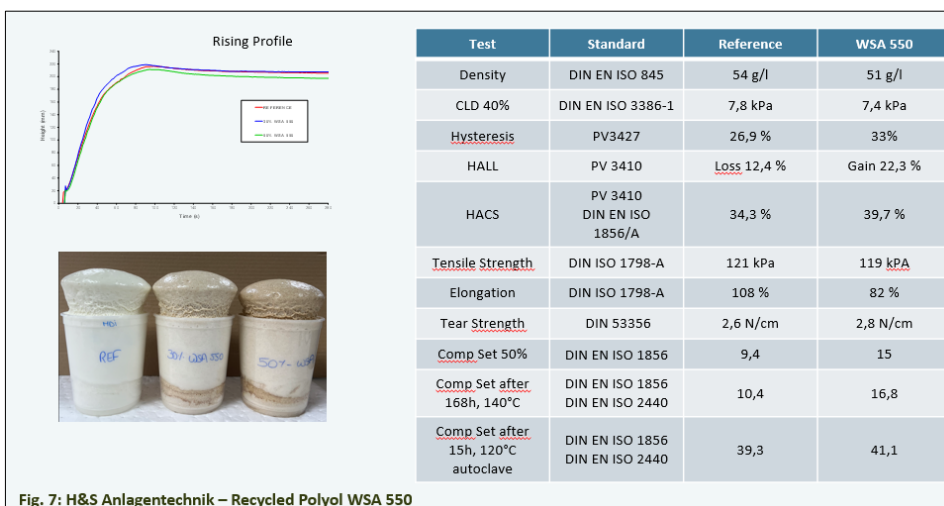


Fig. 7: H&S Anlagentechnik – Recycled Polyol WSA 550

Substance	MDI REF	MDI WSA 550
Formaldehyde (mg/kg)	2,6	3,4
Acetaldehyde (mg/kg)	<BG	0,2
Acrolein (mg/kg)	0,2	0,2
Detection limit (mg/kg)	0,15	0,15

	MDI REF	MDI WSA 550
Test parameter	Measured value in ppm (µg/g)	Measured value in ppm (µg/g)
VOC	82	197
FOG	577	824

H&S Anlagentechnik - Recycled Polyol WSA 551

Lab Sample #	Foam type	MDI	TDI	Added contaminants	Hydroxyl number [mg KOH/g]	Acid number [mg KOH/g]	Amine number [mg KOH/g]	Viscosity [mPa*s] at 25°C	Comment		
WSA 551	Post – Industrial	-	100%	-	36 ± 2	1,4 ± 0,5	9,62 ± 1	10.300 ± 500	Polyol sample – dephasing with high viscosity 'paste' (bottom phase) - Easy to rehomogenize Tested with 50% virgin polyol replacement No specific process issue detected		

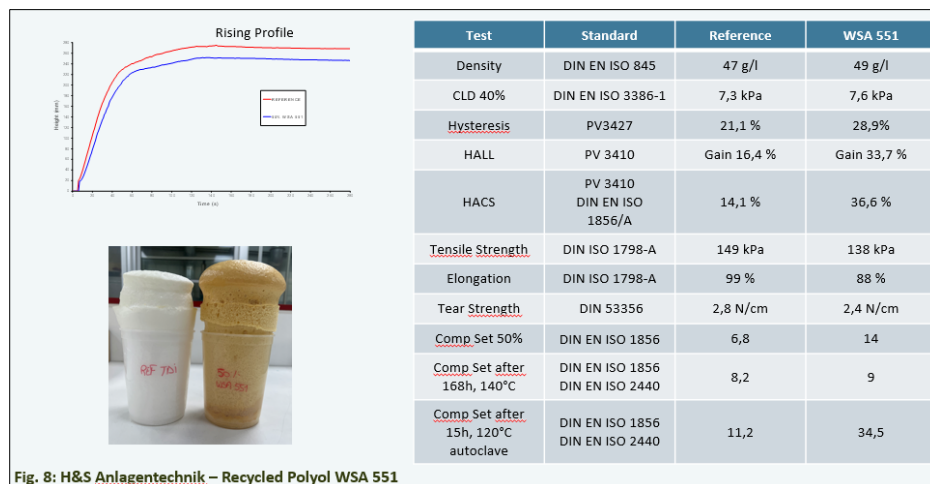


Fig. 8: H&S Anlagentechnik – Recycled Polyol WSA 551

	TDI ref	WSA 551
Test parameter	Measured value in ppm (µg/g)	Measured value in ppm (µg/g)
VOC	117	241
FOG	411	385

H&S Anlagentechnik - Recycled Polyol WSA 553

Lab Sample #	Foam type	MDI	TDI	Added contaminants	Hydroxyl number [mg KOH/g]	Acid number [mg KOH/g]	Amine number [mg KOH/g]	Viscosity [mPa*s] at 25°C	Comment		
WSA 553	Post – Industrial	50%	50%	-	36 ± 2	1,4 ± 0,5	7,3 ± 1	11600 ± 500	Polyol sample – dephasing with high viscosity 'paste' (bottom phase) - Easy to rehomogenize Tested with 50% virgin polyol replacement No specific process issue detected		

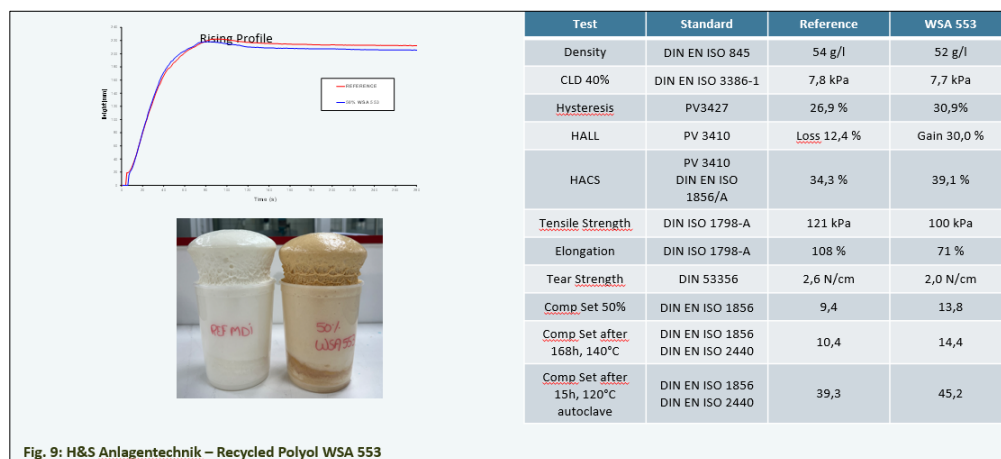


Fig. 9: H&S Anlagentechnik – Recycled Polyol WSA 553

The **rise profiles** of all three r-polyol-based PU foams (WSA 550, WSA 551 and WSA 553) showed approximately **5% recession** relative to the standard formulation. The rise profile of WSA 550 was very similar to that of the standard formulation when only **30% of the standard polyol** was replaced, corresponding to a **closed-loop recycled content** of approximately **9% in the final PU foam**. The physical-property data demonstrate an effect of **r-polyol incorporation**, with the most pronounced differences observed for HALL, HACS and compression set. Apart from these parameters, differences between the standard and r-polyol-based PU foams were within experimental error.

Attention was given to **emissions**. **VDA 278**, a standard emissions test method used in the automotive industry, was **applied to PU foams** based on recycled polyols WSA 550 and WSA 551.

Fig. 10: Impact of r-polyols on emission tests according to VDA278

Testparameter	MDI WSA 550 vs. reference	TDI WSA 551 vs. reference
VOC	+ 140%	+ 106%
FOG	+ 42%	- 6%

Fig. 10 shows an overall significant **increase in VOC and FOG emissions** compared with the reference. The increase is mainly attributable to **individual substances** present at concentrations **below 1 ppm above baseline**, for which no further identification of the chemical structure was available. Traces of **4,4'-methylenedianiline (CAS No. 101-77-9)** were detected in **MDI foam**, while **2,4-toluenediamine (CAS No. 95-80-7)** and **2,6-toluenediamine (CAS No. 823-40-5)** were detected in **TDI foam**. These substances were found in both the **reference and r-polyol-based PU foams**. In addition, **aldehyde-emission testing** was performed for **formaldehyde, acetaldehyde and acrolein**. No differences exceeding experimental error were observed.

H&S Anlagentechnik - Recycled Polyol WSA 573

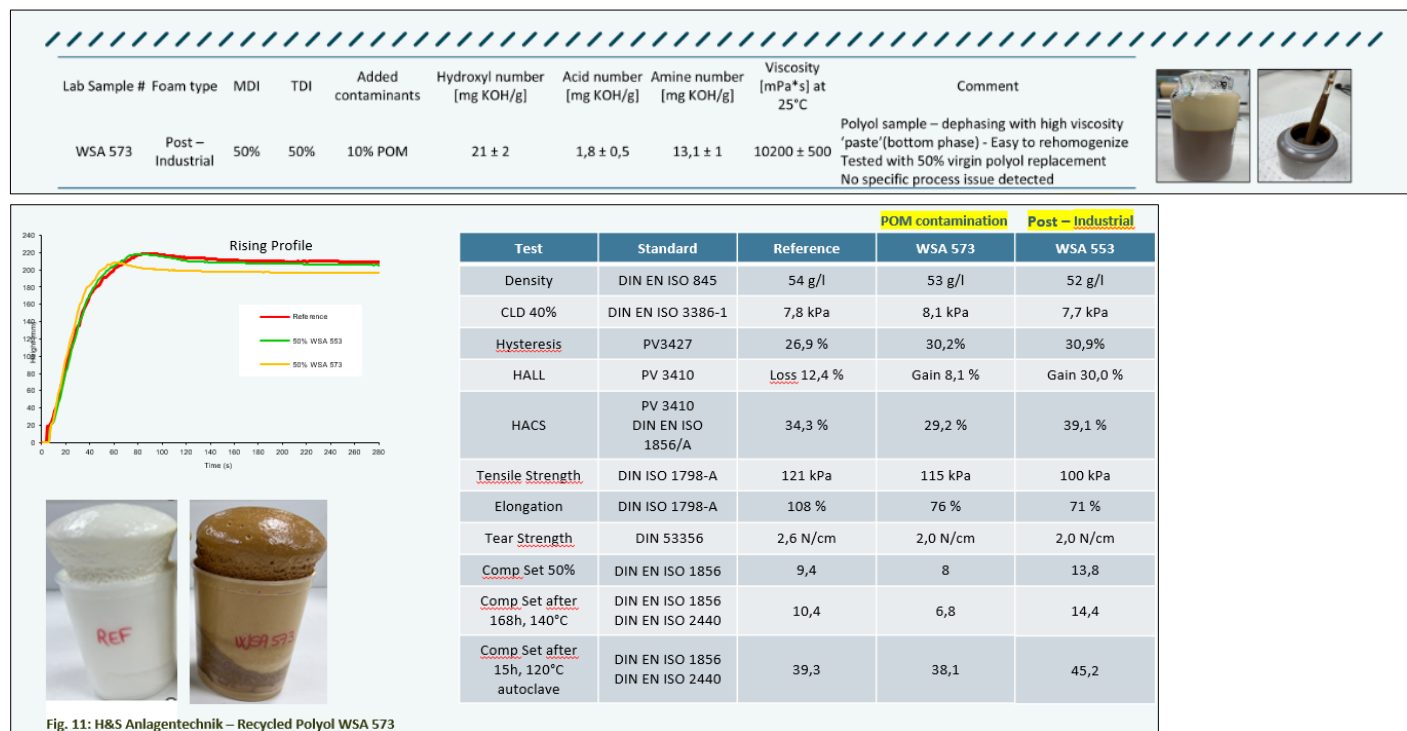


Fig. 11: H&S Anlagentechnik – Recycled Polyol WSA 573

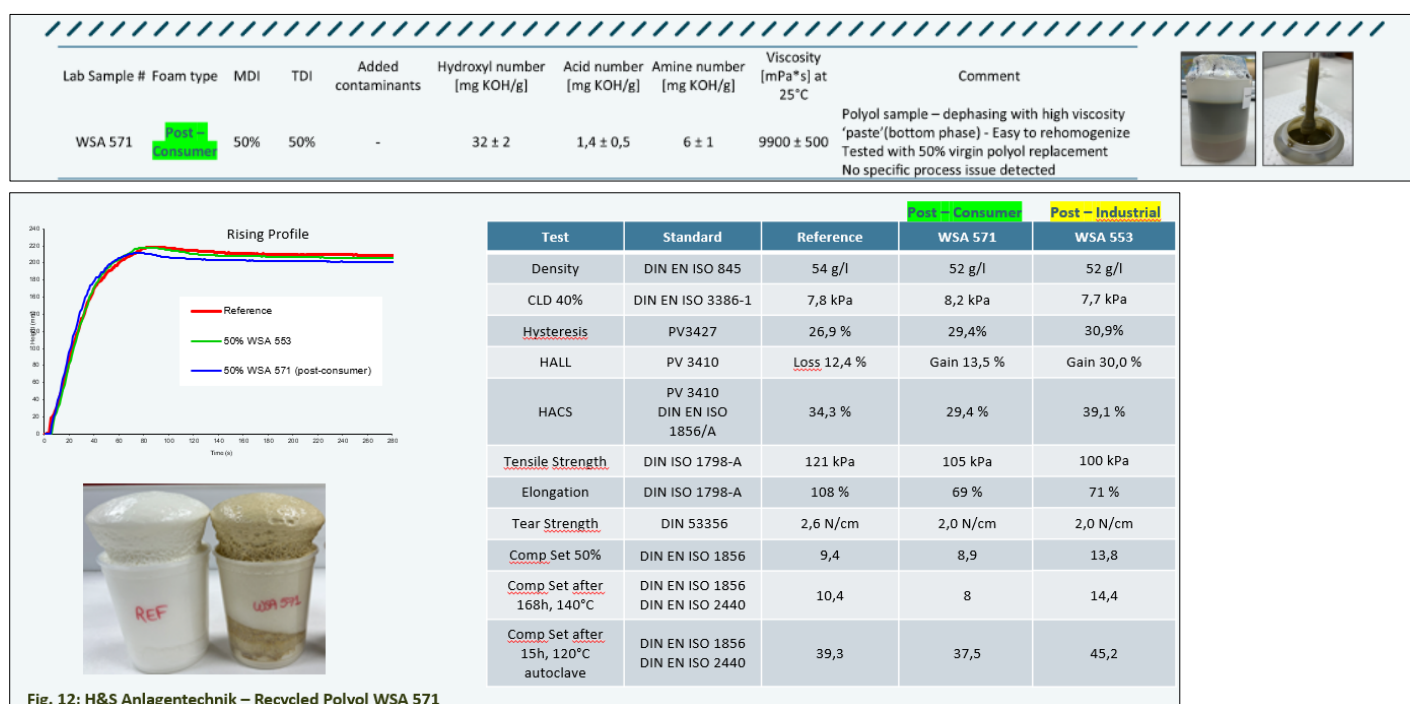
The **POM contamination** had **no significant effect** on the physical properties of the foam. **HALL** appeared to be closer to the value obtained with the standard polyol-based formulation than to that obtained with the WSA 553-based PU formulation.

6.1.2. Post-consumer foam vs. post-industrial foam

Fig. 12 compares, at laboratory scale, PU foams produced using **r-polyols derived from post-consumer and post-industrial PU foams** with a reference formulation. The conventional reference polyol and the two r-polyols, **WSA 571** (derived from post-consumer ELV foam) and **WSA 553** (derived from post-industrial ELV foam), were based on a **50/50 TDI/MDI ratio**.

The **rise profiles** were very similar. Key physical foam properties were evaluated under ambient, dry-heat and humid-heat ageing conditions. Apart from HALL, the **physical properties** of foams derived from post-consumer and post-industrial ELV foam were **very similar**.

H&S Anlagentechnik - Recycled Polyol WSA 571



6.1.3. Performance test of ELV foam

ELV foam was obtained as described in **Chapter 4**, shredded into **PU flakes** by **Federal Eco Foam** and **converted by H&S into r-polyol GWS 090**. The results presented in **Fig. 13** demonstrate that **polyol recovery** from moulded automotive PU seating foam recovered from ELVs is **chemically and technically feasible**. At the top right, **Fig. 13** shows the **foam flakes** that were converted into recycled polyol GWS 090, which had a **recycled content of approximately 40%**. In addition to the technical parameters, **MDA and TDA concentrations** were determined and found to be **relatively low** compared with the CLP hazard-labelling limit of 1,000 ppm for the substances detected.

R-Polyol GWS 090 - Technical Data

Source: Report: "Polyol recovery out of Moulded Automotive PU Seating Foam", H&S Anlagentechnik, August 8th, 2025

Sample No	GWS 090
Hydroxyl number	34 mg KOH/g
Acid number	1,6 mg KOH/g
Amine number	8,4 mg KOH/g
Viscosity	8.300 mPa*s at 25°C
Water content [%]	0,23

Primary aromatic amines : 146,7 ppm [mg/kg]
Extraction with methanol and analyzed using LC-MS

4,4'-Diaminodiphenylmethane	4,7 ppm [mg/kg]
2,4'-Diaminodiphenylmethane	not detected
2,4-Toluenediamine	68 ppm [mg/kg]
2,6-Toluenediamine	74 ppm [mg/kg]

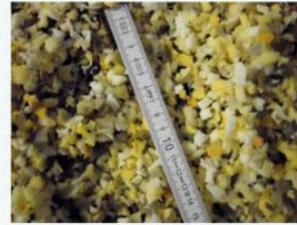


Fig. 13: Technical data of R-Polyol GWS 090

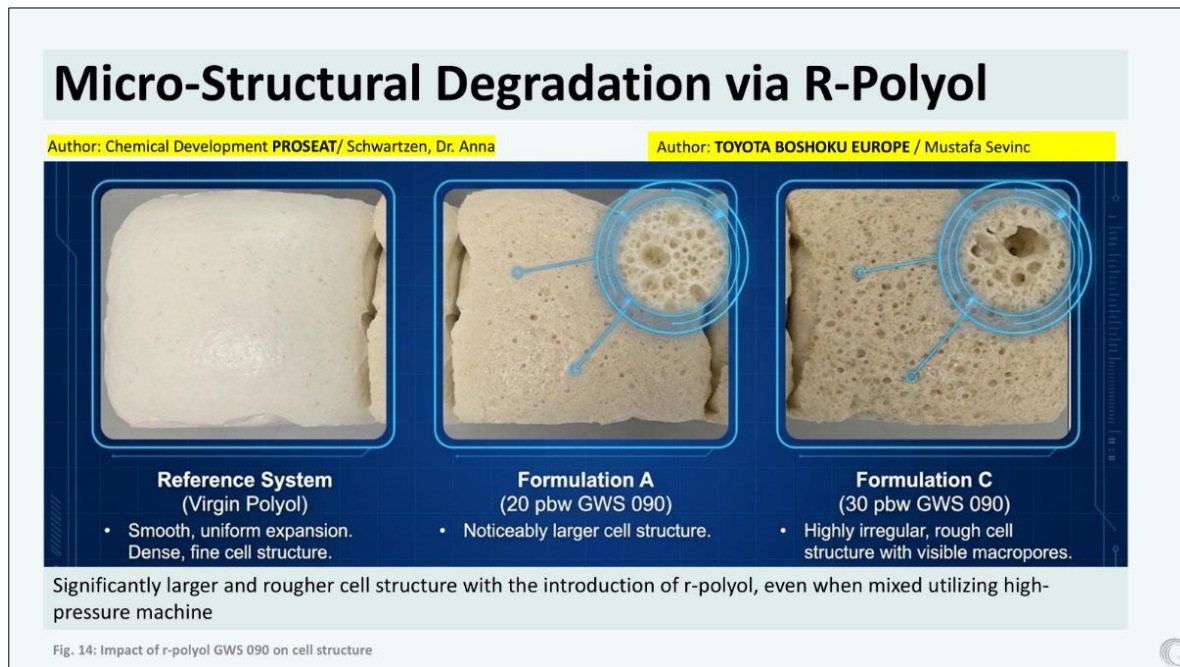
Proseat and **Toyota Boshoku** agreed to test **GWS 090 in MDI technology** in accordance with OEM test standards, replacing **20% and 30%**, respectively, **of the virgin polyol with GWS 090**.

Table 1: Replacement level vs. recycled content (closed loop) in final PU foam	
GWS 090 in MDI control formulation*	App. Recycled content in final PU foam (closed loop)
20%	App. 5 %
30%	App. 7%

* MDI control formulation, see Fig. 6.

Tab. 1 shows the **resulting closed-loop recycled content** of the final PU foam as a function of the replacement level of conventional polyol with r-polyol GWS 090.

Fig. 14 illustrates the **effect of r-polyol GWS 090 on cell structure**. Replacing **20%** of the conventional polyol resulted in a **noticeably larger cell structure**, whereas a **30%** replacement level produced a **highly irregular and coarse cell structure** with visible **macropores**.



Figs. 15–17 present the **physical foam test results** according to **OEM standards** (BMW, VW and Daimler). The figures compare the results with the relevant OEM specifications. Moulded foam was produced at a **density of 60 kg/m³** using three different indices. The properties relevant to the OEM specifications are highlighted in colour.

		Test norm	BMW spec	Reference system – Virgin polyol	Formulation A – 20 pbw GWS 090	Formulation C – 30 pbw GWS 090
Index				90	90	90
Core density	kg/m ³	DIN EN ISO 845		60.2	62.3	60.4
CLD 40%	kPa	DIN EN ISO 3386-1		9.5	9.5	11.4
Hysteresis 70%	%	DIN EN ISO 3386-1		29.8	30.7	34.1
Compression set 50% dry	%	DIN EN ISO 1856-A	< 8	6.1	7.1	7.8
Tensile strength	kPa	DIN EN ISO 1798	≥ 80	127.0	66.9	94.1
Elongation	%	DIN EN ISO 1798	≥ 80	93.5	49.0	59.5
Tear strength (mean)	N/cm	DIN EN ISO 3377-1	≥ 2	3.3	2.6	2.5

- Deterioration of tensile strength, elongation and tear strenght of foams containing recycled polyol vs. reference
- Square blocks results

Fig. 15: Foam Physical Properties acc. to BMW

Physical properties

Acc. TL 52653

			Reference			Formulation A (20% r-Polyol)			Formulation C (30% r-Polyol)		
			80	90	100	80	90	100	80	90	100
Test characteristic	Dimension	Soil	5951	5950	5946	5961	5957	5954	5969	5966	5965
Weight	g		1034,6	1036,9	1033,5	1039,8	1038,3	1040,4	1049,5	1047,2	1044,1
ILD	mm		41,10	26,32	18,86	35,7	23,6	17,8	33,0	22,5	16,6
rel. E.	%		27,90	29,50	30,60	29,80	31,20	32,5	31,3	32,7	32,4
Density	kg/m³		58,94	59,21	59,39	58,62	59,10	59,14	59,25	60,08	59,22
CLD	kPa		6,70	10,13	14,51	7,79	11,76	15,82	8,44	12,50	16,39
rel. E. PV 3427	%		22,71	25,34	28,56	25,01	28,18	31,17	26,60	29,16	32,59
Tensile strength	kPa	≥80	125,9	194,7	228,0	157,7	196,2	218,4	147,6	197,2	214,8
Elongation	%	≥80	118,5	123,0	106,5	112,7	106,0	93,0	112,2	106,1	93,1
Compression set	%	≤8	5,79	5,73	5,48	6,00	5,94	5,98	7,24	6,55	6,65
Tear resistance	N/cm	≥1,9	2,35	3,14	3,50	2,48	2,94	3,45	2,74	3,05	3,46
VW-Heat aging											
Tensile strength	kPa	≥80	156,6	204,7	234,9	170,7	212,6	236,5	155,7	186,6	221,3
Elongation	%	≥80	124,6	118,9	108,5	113,6	109,3	96,9	106,3	97,5	92,0
Humid aging											
4th CLD	%	+10/-30	2,86	-7,65	-15,23	3,11	-8,81	-15,28	8,30	-6,70	-13,59
Compressive set	%	≤1,5	17,68	21,12	23,62	12,52	15,99	20,20	17,65	20,02	20,67
Tensile strength	kPa	≥80	142,1	162,5	186,4	148,0	193,6	225,9	139,5	184,9	219,7
Elongation	%	≥80	147,6	149,3	135,0	122,2	130,4	112,6	117,4	121,0	119,8
Burning behavior	mm/min	≤100	0	0	0	0	0	0	0	0	0

Fig. 16: Foam physical properties acc. to VW

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- Hardness increase by adding r-Polyol content
- Hysteresis gets worse
- Compression set gets worse, but positive impact after humid aging
- Tensile strength in standard conditions and heat aging similar; after humid aging values increase
- r-Polyol has negative impact on elongation at all conditions

Physical properties

Acc. DBL 5452/ DBL 1250

				Reference			Formulation A (20% r-Polyol)			Formulation C (30% r-Polyol)		
			Index	80	90	100	80	90	100	80	90	100
Test characteristic	Dimension	DBL 5452	DBL 1250	5951	5950	5946	5961	5957	5954	5969	5966	5965
Density	kg/m³			58,98	59,38	58,77	58,63	58,69	58,83	59,40	59,77	59,23
CLD	kPa			6,31	9,54	12,72	7,25	10,65	13,65	7,66	10,92	14,28
Tensile strength	kPa	≥100	≥100	210,5	227,8	248,5	182,7	232,7	263,8	179,5	189,5	231,9
Elongation	%	≥90	≥90	136,0	121,4	109,5	115,4	110,6	101,1	116,8	88,2	88,7
Compression set	%	≤7	≤10	5,79	5,73	5,48	6,00	5,94	5,98	7,24	6,55	6,65
MB- humid aging												
4th CLD	%	≤50	≤50	-41,45	-48,53	-49,55	-28,52	-35,87	-39,89	-27,74	-34,90	-42,55
Compression set	%	≤21	≤25	38,39	41,43	42,15	36,53	38,89	39,17	39,10	41,12	41,55
Tensile strength	kPa			32,7	51,2	73,7	74,3	106,5	148,9	70,8	96,4	151,5
Elongation	%			40,6	60,1	67,2	94,0	104,4	121,8	74,7	92,1	106,6
Tensile strength	%	≤40	n.a.	-84,47	-77,52	-70,34	-59,33	-54,23	-43,56	-60,56	-49,13	-34,67
Elongation	%	≤10	n.a.	-70,15	-50,49	-38,63	-18,54	-5,61	20,47	-36,04	4,42	20,18
MB- heat aging												
4th CLD	%	≤40	≤50	-47,74	-47,81	-45,48	-45,54	-44,42	-41,75	-42,04	-40,98	-39,89
Compression set	%	≤8	≤10	6,81	7,14	8,50	8,34	8,63	10,81	8,82	10,55	11,71
Tensile strength	kPa			99,7	161,8	188,2	116,1	144,2	194,5	104,7	139,1	183,7
Elongation	%			114,7	116,2	105,6	101,4	92,8	94,2	91,9	90,0	88,0
Tensile strength	%	≤40	n.a.	-52,6	-29,0	-24,3	-36,5	-38,0	-26,3	-41,7	-26,6	-20,8
Elongation	%	≤40	n.a.	-15,7	-4,3	-3,5	-12,1	-16,1	-6,8	-21,3	-2,0	-0,8

Fig. 17: Foam physical properties acc. to Daimler

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- Hardness increase by adding r-Polyol content
- Elongation gets worse
- Hardness loss after aging positively influenced
- Tensile strength and elongation after aging not included anymore in new standard DBL 1250
- But measured for comparison to part 1 of this study
- Compression set partially out of spec after heat aging

Because the high solids content of **r-polyol GWS 090** created limitations on the pilot plant machine, some PU blocks were prepared manually in the laboratory. **GWS 090 was not tested in TDI technology** due to the **high solids content** of this particular batch, which caused processing limitations and indicated the need for **further process optimisation**. The solids were analysed by **infrared spectroscopy** and indicate that the solids contain **residual polymer fragments** which have not been completely dissolved in the chemical recycling process.

Fig. 18 presents findings regarding the **chemical emissions** of polyurethane foams with **recycled polyol GWS 090**.

Emission Test Results

	VOC ISO [µg/m ³ /kg]	Formaldehyde [µg/m ³ /kg]	Acetaldehyde [µg/m ³ /kg]	VOC VDA278 [µg/g]	FOG VDA278 [µg/g]
Reference	400-420	150-200	15-20	200-220	130-400
From A	> 400	110-150	15-20	120-260	120-420
Form C	> 550	140-180	16-20	90-330	90-460

Test	Standard
Chamber Test	GS 97014-3 BMW
VOC	ISO 16000-6
Aldehydes	ISO 16000-3
VOC, FOG	VDA278

- Emission tests of PU foams with 20% and 30% replacement of conventional polyol by GWS 090.
- Standard OEM tests methodology
- Emission results are not perfect
- No clear trend regarding the impact of using r-polyol on emissions.

Fig. 18: Emission results

Toscana Gomma conducted **chamber tests and VDA 278 testing** to evaluate the effect of replacing conventional polyol with recycled polyols on **emissions and air quality**. The available data indicate that the **emission performance** of these materials is **currently inconsistent** and **does not meet the desired benchmarks**. Furthermore, **no definitive correlation could be established** between the **use of recycled polyols** and a **specific increase or decrease in volatile organic compound emissions**. Robust conclusions regarding the effect of recycled polyols on foam emissions will require **more comprehensive emission testing using r-polyols** derived from ELV foam.

In summary, the comprehensive evaluation of different r-polyols derived from post-industrial and post-consumer/ELV foam produced **promising results**. Many **physical properties** already meet **industry requirements**, demonstrating the underlying **potential of recycled polyols**. Nevertheless, **several areas require further improvement** in relation to **depolymerisation**:

- **R-polyol**

Further **improvement in r-polyol quality** is required, including **odour management** to meet OEM specifications. In addition, r-polyols must be **free of solids** that adversely affect the processability of foam production on high-pressure moulding equipment. The concentration of **primary aromatic amines** must also be controlled.

- **Foam formulation**

Further **optimisation and adaptation of PU formulations** are required.

- **Physical foam properties**

The test results **do not indicate a consistent overall effect** of recycled polyol on **foam properties**, apart from **cell structure**. Certain foam properties are affected, but the relevance and magnitude of these effects depend on the applicable **OEM specification**.

- **Foam emissions**

No clear trend was identified regarding the **effect of r-polyol use on foam emissions**. This finding should, however, be confirmed through replicate test runs.

6.2. HTC Process

6.2.1. Interest of the technology - Why focus on ASR?

Current **chemical and mechanical recycling processes** require **clean and dry PU foam**. Obtaining feedstock of this quality requires PU foam to be **collected under conditions that preserve its recyclability**. **Hydrothermal carbonisation (HTC)** may provide an **alternative recycling route**. In nature, **coalification** occurs under relatively mild conditions, **converting biomass into coal** over geological timescales of millions of years. To achieve a comparable conversion of biomass into a coal-like product within a technically practical timeframe, the **HTC process** is operated under more severe conditions, reducing the **reaction time** to a few hours.

The HTC process can **tolerate highly complex mixtures of materials** as feedstock. The resulting densified HTC char can, for example, be **converted into syngas** (CO, H₂) by **direct gasification** and subsequently used as feedstock to produce new chemical intermediates. Alternatively, **pyrolysis** produces **pyrolysis oil and carbon black**. The **oil** may be used as feedstock in **cracking processes**, while the **carbon black** may **substitute certain carbon-black materials** derived from fossil resources.

Fig. 19 provides a **comparison of the different recycling routes**, required feedstocks and products.

Why focus on Automotive Shredder Residue (ASR)?					
Pre-treatment	Recycling process	Plastics separation	Feedstock	Availability of Feedstock	Product
Before shredder	Chemical recycling	Manual dismantling / Machine-assisted dismantling + post-cleaning	Clean and dry Polyurethane	limited	R-polyols
	Mechanical recycling				PUR flakes
After shredder	HTC process + Pyrolysis	No need for separation	Automotive Shredder Residue (ASR)	unlimited	Pyrolysis oil + carbon black
	HTC process + Direct gasification				Syngas (e.g., CO, H ₂)

Fig. 19: Why focus on Automotive Shredder Residue ?

6.2.2. Work performed

The study for **EUROMOULDERS**, conducted at the **Environmental Campus Birkenfeld** (Prof. Kirsch, Trier University of Applied Sciences, Germany) under the leadership of **NEVEON**, was designed as an initial investigation into whether HTC technology for the pre-treatment of mixed PU-containing waste could also be applied to **unsorted Automotive Shredder Residue (ASR)**, thereby enabling subsequent **large-scale industrial direct gasification** or **pyrolysis**. The HTC technology for ASR was developed through cooperation between NEVEON and the Environmental Campus Birkenfeld.

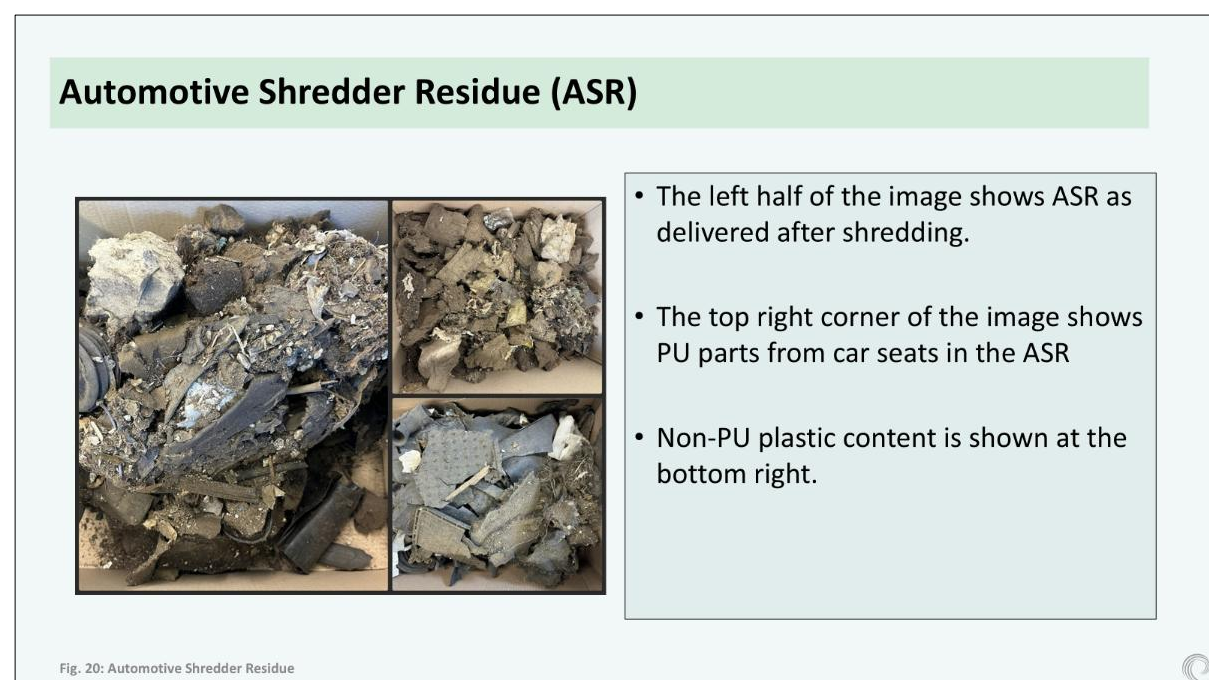


Fig. 20 shows the **ASR as received after shredding** on the left-hand side. The ASR was **manually pre-sorted** on a preliminary basis to estimate the proportions of PU and non-PU plastics. The upper-right image shows **PU foam components recovered from car seats**, while the lower-right image shows the non-PU plastic fraction.

The ASR-HTC trial results demonstrate that **unsorted shredded ASR** can be treated **using HTC technology** to produce a **dry, free-flowing carbonaceous HTC product (Fig. 21)**. Depending on the actual PU content of the ASR, other readily available end-of-life PU streams can be blended in.

HTC-Charcoal based on ASR-feedstock



- Picture of HTC-charcoal based on ASR-feedstock
- A volume reduction of ASR of app. 85%
- Density increase from app. 105 kg/m³ to app. 560 kg/m³

Fig. 21: HTC-Charcoal

An **ASR volume reduction** of approximately **85%** was achieved, together with an **increase in density** from approximately 105 kg/m³ to approximately **560 kg/m³**. These changes should **facilitate downstream use** of the treated ASR. The stakeholders subsequently decided to discontinue work on the HTC process because of resource constraints.

7. Summary

7.1. Challenges in Material Recovery

- **Storage issues:** ELVs stored outdoors frequently develop wet interiors, which can further degrade the PU foam.
- The principal challenge for recycling is **obtaining high-quality feedstock**. Current shredder light fraction (SLF) is often **contaminated with oils, metal dust and other plastics**, making it unsuitable for conventional **mechanical or chemical recycling**.

7.2. Dismantling

- **Manual dismantling** is the **most effective** method for obtaining **clean foam**, but it is time-consuming.
- **Machine-assisted dismantling is faster**, but **additional post-cleaning is required** to remove components such as cables, fleece and airbag detectors.

7.3. Recycling Technologies and Findings

The report evaluates three primary recycling pathways:

- **Mechanical Recycling:**

Cleaned ELV foam flakes that are free from metal components, hard plastics, fleece and other contaminants can be **bonded to produce sports mats**. Trials at **Federal Eco Foam** demonstrated that these flakes can be **processed in the same manner as standard foam flakes**, with no identified issues relating to **legacy substances** or **compounds** on the **REACH Candidate List**.

- **Chemical Recycling (Depolymerization)**

Post-industrial automotive PU foam can be chemically recycled into **r-polyol**. MDI and TDI foams were successfully processed, but contaminants such as **EPP and PES fleece reduce process performance**. **Replacing up to 50% of virgin polyol** was feasible, achieving **15–19% recycled content** in the final foam. Physical properties remained largely comparable, while **VOC/FOG emissions increased**.

Performance testing indicates that **replacing 20–30% of virgin polyol with post-consumer r-polyol GWS 090** in automotive-seat formulations is **technically feasible**, resulting in a **closed-loop recycled content** of approximately **5–7% for MDI**. Emission testing showed varying results. No clear correlation between the use of recycled polyol GWS 090 and increased VOC/FOG emissions could be

established. Further optimisation is required, particularly with respect to **odour management** and the **cell morphology** of r-polyol-based foams.

- **Thermochemical Recycling (HTC Process)**

Hydrothermal carbonisation (HTC) was investigated as a potential treatment route for **unsorted Automotive Shredder Residue (ASR)**. Preliminary trials demonstrated an **ASR volume reduction of approximately 85%**, producing a **dry, free-flowing carbonaceous material** suitable for subsequent **gasification** or **pyrolysis**.

8. Conclusions

Mechanical and chemical recycling of PU foam from ELVs is technically feasible. However, current processes for **converting PU foam into r-polyols** require **clean and dry** PU feedstock. **Improvements** are therefore needed in the **storage and dismantling of ELVs** to enable the recovery of sufficiently **high-quality and process-ready PU foam**. Improved **design for dismantling** could facilitate **more efficient recovery of clean foam** while **reducing material losses**.

8.1. Future work

- Further work should focus on **improving r-polyol quality** and **optimising replacement levels** so that stringent OEM specifications can be met without compromising performance, odour or emissions.
- Improved **car-seat design for dismantling** is also required to accelerate the dismantling process.
- The **multi-material construction** of car seats should also be addressed, as it creates difficulties when sorting the different plastics used in seat components.
- Although **HTC/direct gasification** and **HTC/pyrolysis** were investigated only to a limited extent, these processes warrant greater consideration in the search for the most appropriate recycling routes for PU foam from end-of-life vehicles (ELVs).

9. References

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10. Definitions, acronyms, abbreviations

- ASR – Automotive shredder residue
- Comp. Set – Compression Set
- ELV - End-of-Life Vehicle
- EPP - Expanded polypropylene
- HACS – Humid aged compression set
- HALL – Humid aged load loss
- HR-MDI foam - High-resilience flexible polyurethane foam using diphenylmethane diisocyanate (MDI)
- HR-TDI foam - High-resilience flexible polyurethane foam using toluene diisocyanate (TDI)
- HTC-technology - Hydrothermal carbonization (HTC) is a chemical process for the conversion of organic compounds to e.g., synthesis gas or liquid petroleum precursors
- POM – Polyoxymethylene
- PU – Polyurethane
- R-polyol – Recycled polyol
- SLF - Shredder light fraction

11. Acknowledgments

The joint work of Euro-Moulders would not have been possible without the support of individuals from the organisations listed below:

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EURO-MOULDERS is the European Association of Manufacturers of Moulded Polyurethane Parts for the Automotive Industry. Our members produce moulded polyurethane foams for seat cushions in 28 plants in 13 countries. They collectively employ over 10,000 people. The EU's total production of moulded foam for the automotive sector is around 150,000 tonnes per year. Moulded polyurethane (PU) foam, thanks to its unique properties, is today by far the preferred cushioning material for automotive seating, with a market share of well over 90%.