Improved Performance for Hydraulic Seals from Thermoplastic Polyurethane

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Management Summary

Seal design engineers and end users are continually seeking improved sealing systems and materials. This paper describes the potential of a new thermoplastic polyurethane (TPU) material to deliver improvements in pressure, speed and temperature capability, which are presented as comparisons to proven industry standard materials. Performance is demonstrated by virtue of test bench results of seals made from MDI-, PPDI- and NDI-based materials.

Laboratory results of temperature scanning stress relaxation (TSSR) testing will be reviewed to show that this high-performance TPU can compete with cured polyurethanes while utilizing existing TPU technology and tools to maintain a commercially competitive product.

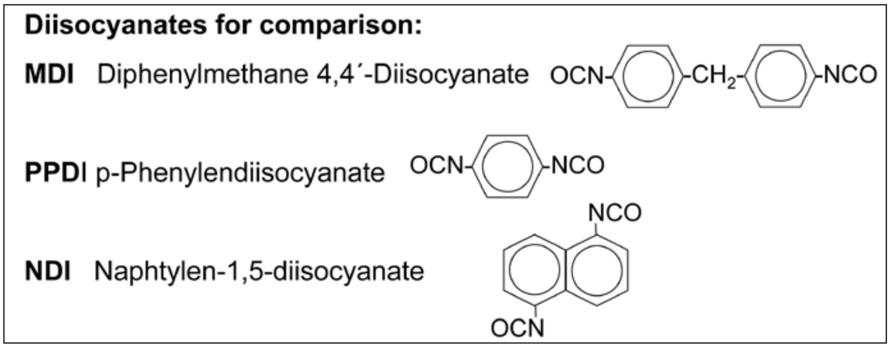


Figure 1—Comparison of isocyanates used in construction of thermoplastic polyurethane.

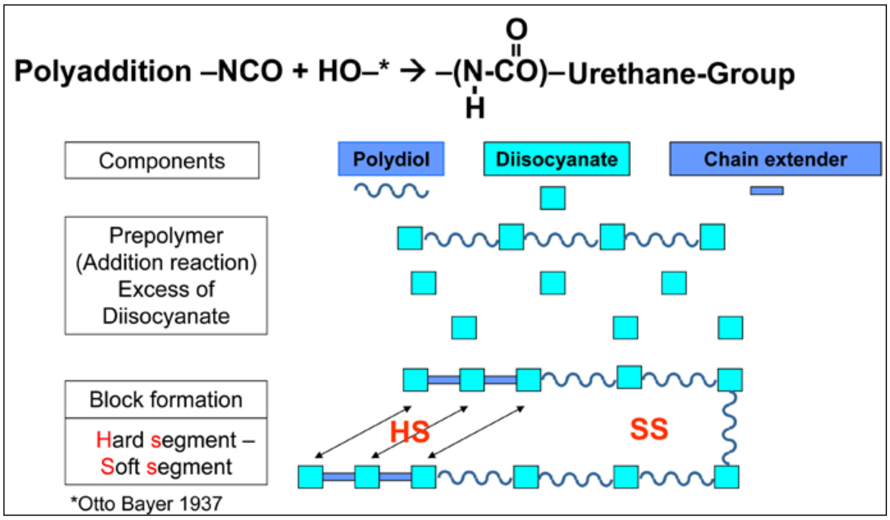


Figure 2—TPU synthesis via pre-polymer process.

Introduction

Thermoplastic polyurethane has been established for more than 30 years as a standard material for dynamic seals in hydraulic systems. TPU's outstanding mechanical properties—in combination with its straightforward thermoplastic molding process—have ensured this market position. Furthermore, the variety of available polyurethane chemistry allows an adjustment of the material properties to meet a range of different requirements.

Most commercially available TPU materials produced by reputable seal manufacturers are based on MDI. (*Editor's Note: MDI (diphenylmethane diisocyanate) is a polyurethane resin used as spandex fibers and for bonding rubber to rayon. It is used in the production of polyurethane lacquers, foam plastics, rubbers, thermal insulators and glues.*) One specific seal manufacturer is offering TODI-based (3, 3´-dimethyl-4, 4´-biphenyldiisocyanate) TPUs as standard materials.

The temperature range specified for MDI materials, except for special types, is usually 35–110°C—a temperature range that is suitable for use with many standard hydraulic oils.

However, the demand to increase power density in hydraulic systems has led to higher pressure requirements and has driven the temperatures up in hydraulic cylinders, along with OEM and end user requirements for longer life. Temperature capabilities for sealing materials are now required to be within 120–130°C.

With this in mind, can this temperature requirement be satisfied with an MDI-based material or must you go to a material based on PPDI (p phenylenediisocyanate) or NDI (naphtylene-1, 5-diisocyanate)? The specified continuous temperature application limit of the NDI-based material is 135°C (higher for short periods); NDI is commercially available.

Or is it necessary to develop a material with an alternative diisocyanate optimized for sealing applications? A major problem with that approach is that the price for such a material would be several times higher than an MDI.

Ingredients of TPU material. Figures 1 and 2 show the basic raw materials for TPU synthesis as well as the diisocyanates used for the reference materials discussed in this paper. TPU consists of 3 basic ingredients:

Polydiol = $HO\text{-}R_1\text{-}OH$ (long chain)
Diisocyanates = $OCN\text{-}R_2\text{-}NCO$
Chain extender = $HO\text{-}R_3\text{-}OH$ (short chain)

TPU materials tested. Four materials were produced and tested:

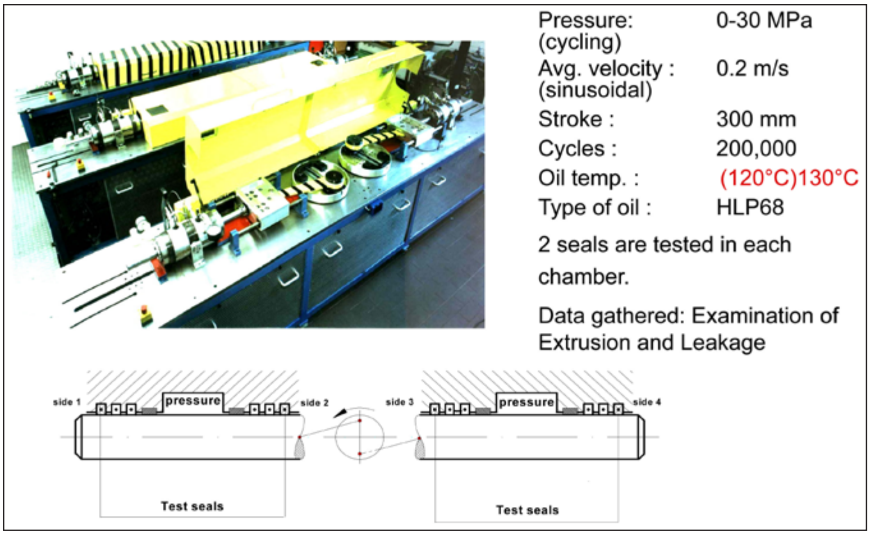
- A proven, standard hydraulic TPU based on MDI
- A novel, high-performance TPU for hydraulic seals, also based on MDI
- A commercial material based on PPDI
- A commercial material based on NDI

Test sheets and seals in an RU9 U-Cup profile were produced for testing in a size to suit a 50 mm diameter rod.

(*Authors' Note: See Appendix, Table 1, for physical properties of these four materials.*)

Test equipment and method. Figure 3 shows an outline of the test arrangement with service conditions that are specified to test the limits of the seals in order to obtain a good understanding of their capabilities. To protect pumps against high temperatures, low-viscosity oil—Shell Tellus 6—was chosen over the more common ISO VG 46. **Oil condition was carefully monitored due to the high time temperature load to ensure always same test conditions.**

Note that pressure is cycled with the stroke, meaning that seals at positions 1 and 4 are exposed to a pressurized instroke, whereas seals at positions 2 and 3 are exposed to a pressurized out-stroke. For this reason seals at positions 1 and 4

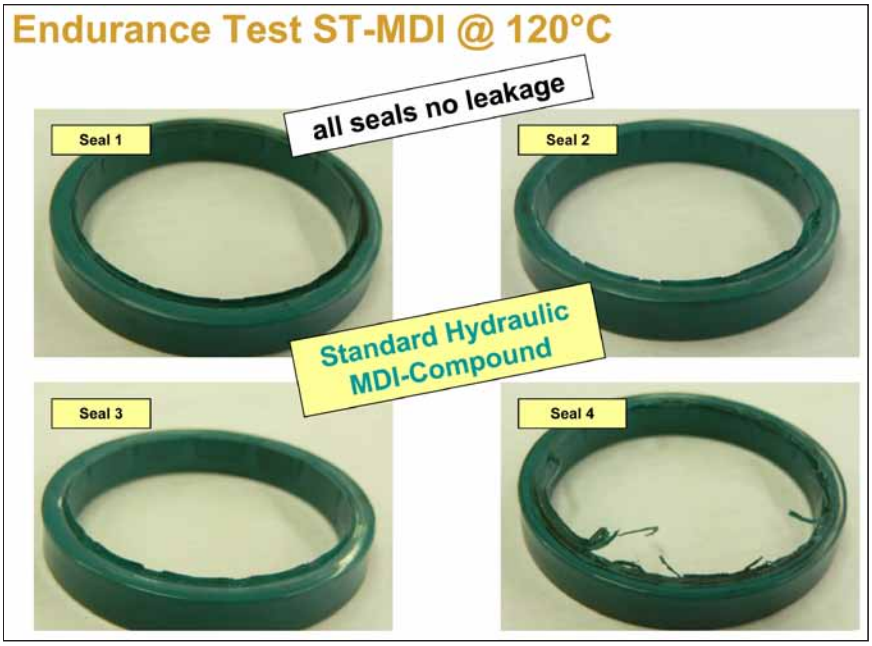


Pressure: (cycling)	0-30 MPa
Avg. velocity : (sinusoidal)	0.2 m/s
Stroke :	300 mm
Cycles :	200,000
Oil temp. :	(120°C)130°C
Type of oil :	HLP68

2 seals are tested in each chamber.

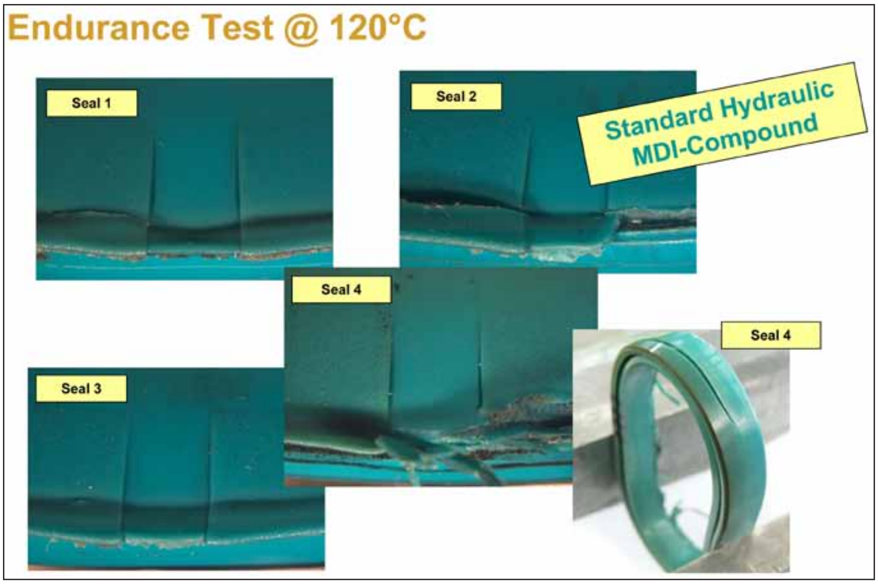
Data gathered: Examination of Extrusion and Leakage

Figure 3—Test arrangement for cycle testing of hydraulic seals.



Endurance Test ST-MDI @ 120°C

Figure 4—Standard MDI compound, 120°C.



Endurance Test @ 120°C

Figure 5—Details from Figure 4.

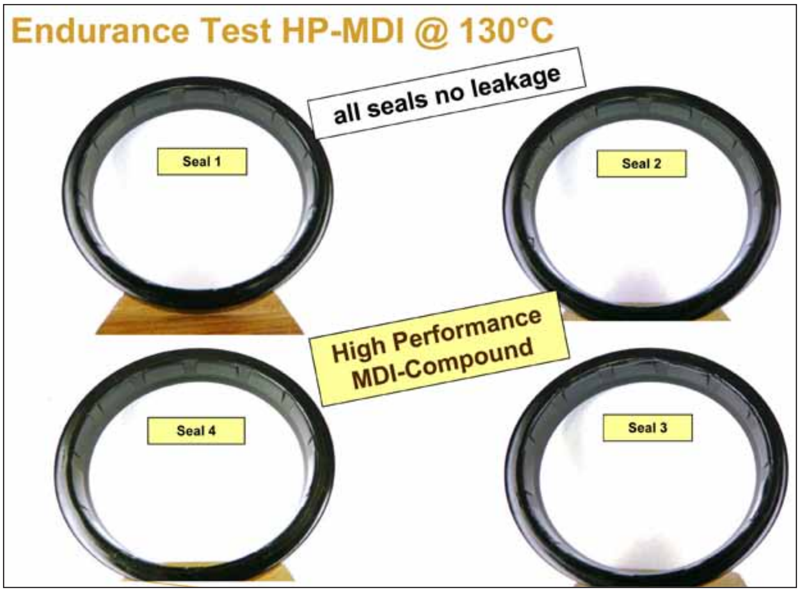


Figure 6—High-performance MDI compound, 130°C.

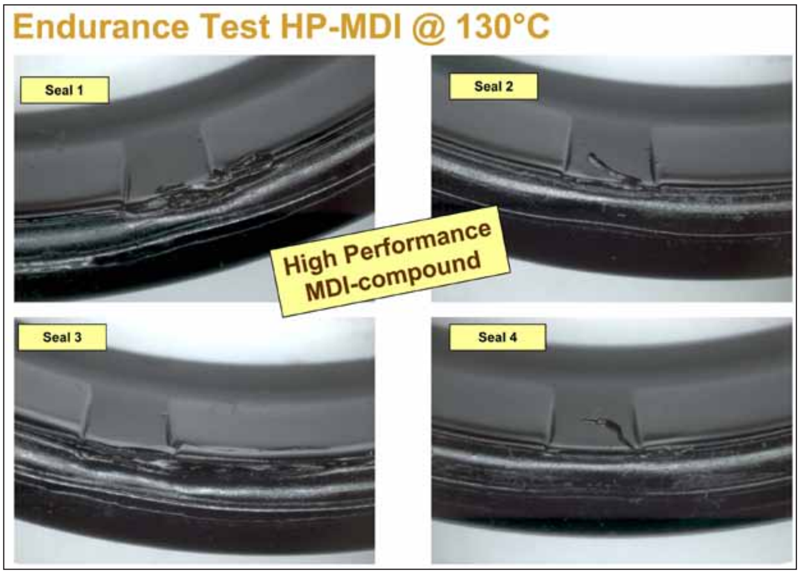


Figure 7—Details from Figure 6.

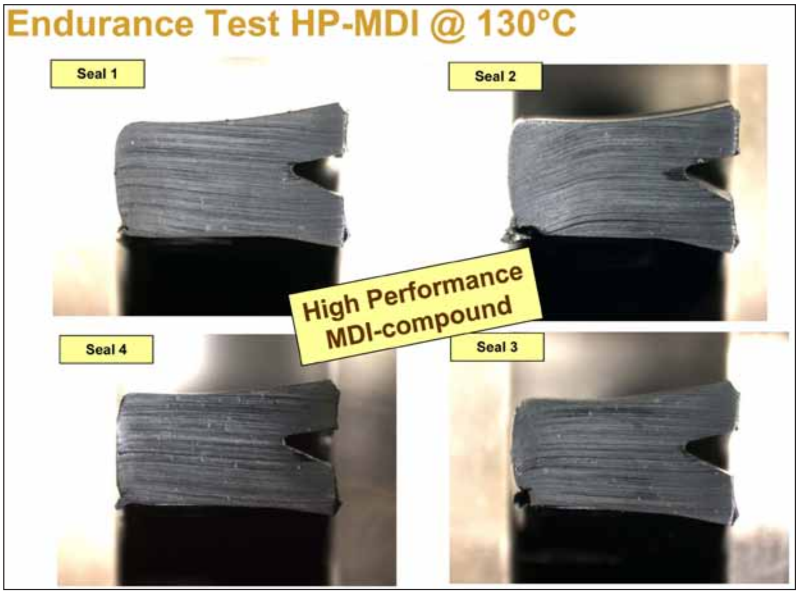


Figure 8—Cross-sections of seals in Figure 6.

are considered to be most representative of typical service conditions.

Test results. First we will review the results of the proven standard hydraulic TPU compared with the newly developed, high-performance TPU—both MDI based.

Figure 4 shows seals made from the standard hydraulic MDI-based material after a test run at 120°C continuous temperature (Fig. 5).

A considerable degree of extrusion is visible, especially on seal 4. Although the test run was finished without leakage, the limit of the seals is visible.

Figures 6 and 7 show the corresponding seals made from the MDI high-performance TPU after the test run, conducted at 130°C continuous temperature. Note that the close-ups in Figure 7 and the profile sections shown in Figure 8 display very limited extrusion; again, no leakage and the seals remain completely functional.

In comparing the two materials, the high-performance MDI material is clearly superior, despite the 10°C increase in test temperature. This is evidenced also by comparing the change of interference (Appendix, Fig. 17) when comparing all four TPU compounds.

After the direct comparison between standard- and high-performance MDI compounds, next is a comparison with the test results of the RU9 U-Cup from the PPDI- and NDI-based materials.

Figures 9–11 show images of seals of a commercially available PPDI compound tested at 110°C.

Another way to evaluate performance is to look at the permanent loss of seal interference after testing. This interference is vital to seal performance at both low and high pressures, and while some loss of interference is always expected, excessive loss can lead to premature failure.

By comparing the seals from the commercial PPDI compound tested at 110°C with those of the high-performance MDI compound—tested at 130°C—a comparable level for the loss of interference is visible.

Figures 13–15 contain test results of seals made of commercial NDI compound, having completed the test run at 130°C continuous temperature.

Despite its good properties profile, the commercial NDI material did not exceed the high- performance MDI material in terms of extrusion resistance—even at a high temperature of 130°C.

High-temperature properties. So what is the difference-maker in the performance of the sealing material?

Table 2 (Appendix) shows the physical properties of these four materials at higher temperatures, as well as the key points from the DMA analysis that are detailed in Figure 16 (Appendix).

The NDI material shows the best tensile strength values and the highest softening temperature (see Appendix, Figure 16, Onset 2). The high-performance MDI material follows with a softening point approximately 2°C lower. The PPDI material shows with 7.5°C less—a significant difference. However, the storage modulus of the high-performance MDI material in the upper temperature range is about 40 percent higher.

The DMA curve confirmed the known benefits—good visco-elastic properties—of NDI material with a very steep drop of the curve in the glass transition temperature, compared to the more gradual transition of the PPDI and high-performance MDI materials.

TSSR testing. Brabender TSSR testing was employed to characterize the new high-performance MDI material and to compare it with published data on other thermoplastic and thermosetting sealing materials. (*Editor's Note: Temperature scanning stress relaxation is an anisothermal stress relaxation test method that also enables conventional isothermal relaxation measurements.*) Figure 17 (Appendix) shows that it appears to be superior to the other thermoplastic polyurethane materials in terms of T50 failure temperature and rubber index value; i.e., a measure of stress relaxation with varying temperature. A theoretically perfect material would have a rubber index of 1.

Summary

A comparison of endurance test shows that a high-performance, MDI-based TPU—optimized specifically to the needs of a highly-loaded hydraulic seal in regard to temperature and

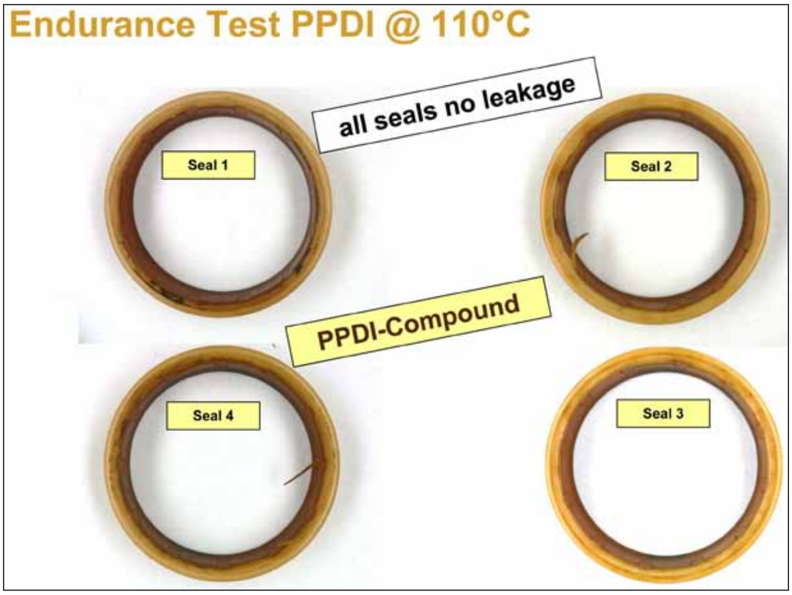


Figure 9—Commercial PPDI compound, 110°C.

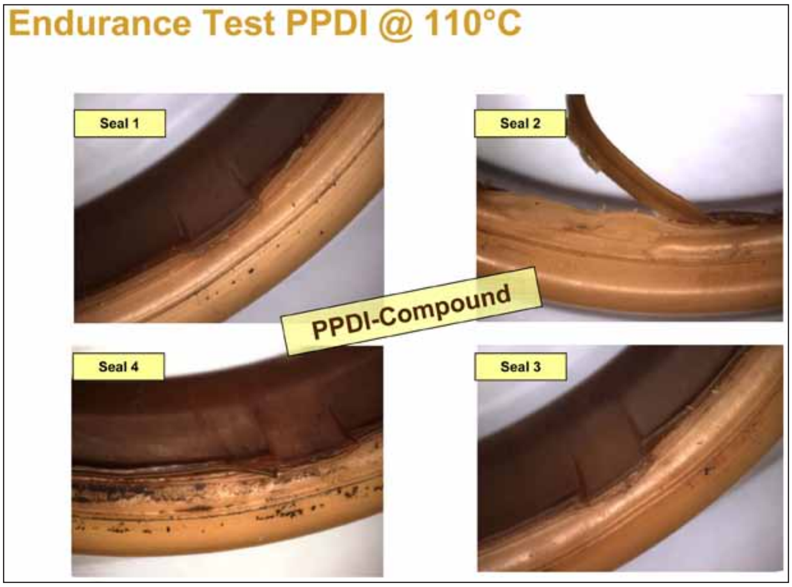


Figure 10—Details from Figure 9, partial extrusion visible on seals 2 and 4.

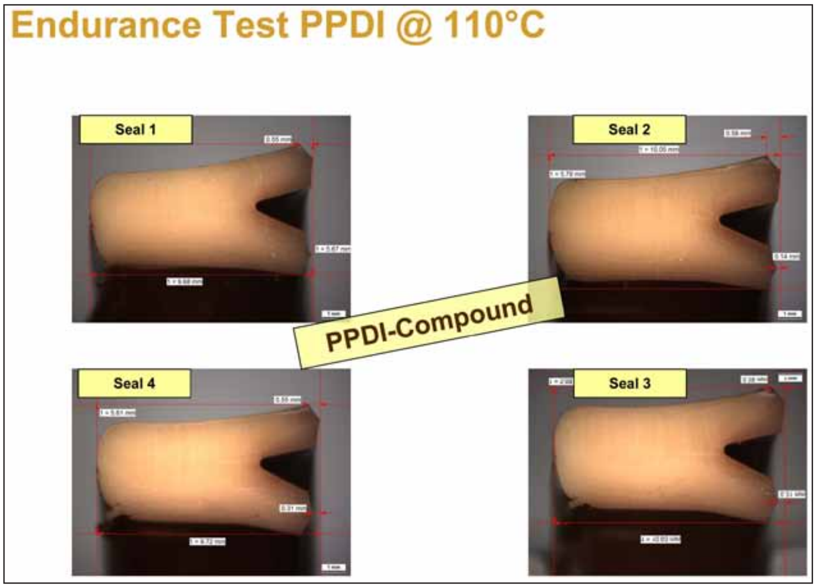


Figure 11—Cross-sections of seals from Figure 9; again, extrusion is clearly visible.

pressure—can out-perform a range of common TPU seal materials, including conventional MDI and commercially available NDI- and PPDI- based TPUs.

As a final comparison—Figure 18—shows the change of interference of test seals from all four materials run at specified temperatures in the study. Once again the high-performance MDI material shows its superiority—even when tested at temperatures higher than the others.

The high-performance, MDI-based material also showed benefits in extrusion resistance, storage modulus and TSSR performance. As a value-added benefit, the MDI material can be processed by using the same tools and methods as the standard MDI material—thus enabling a simple seal upgrade for high-temperature applications.

Conclusion

It has long been assumed that NDI-based materials were required to ensure the stable, high-temperature performance of polyurethane hydraulic cylinder seals. But with out-of-the-box material design—and evaluation methods that closely replicate real-world working conditions—it has been demonstrated that a specially developed, MDI-based material can perform extremely well. This in turn allows for production of commercially and technically competitive, high-performance seals.

Acknowledgments. *The authors wish to express their thanks to Dipl.-Ing. Frank Fuchs of Brabender GmbH & Co. KG, Duisburg, Germany, for permission to use Brabender's TSSR data on comparative sealing materials.*

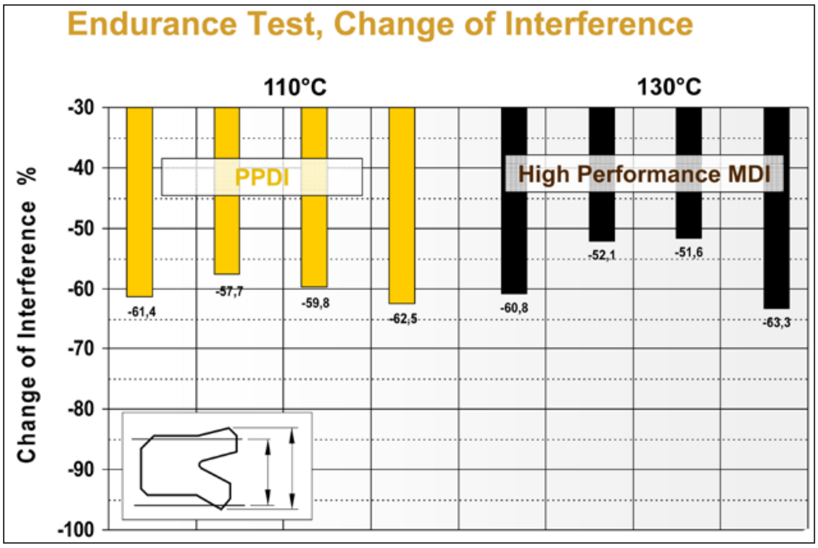


Figure 12—Comparison of the change of interference between PPDI and high-performance MDI materials.

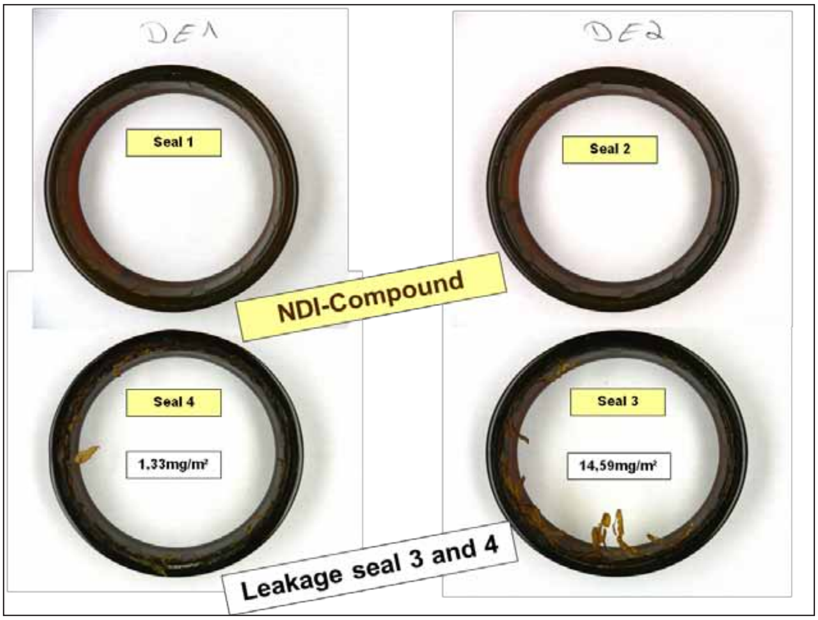


Figure 13—Commercial NDI-based material, 130°C; note the thick, broken extrusion on seals 3 and 4.

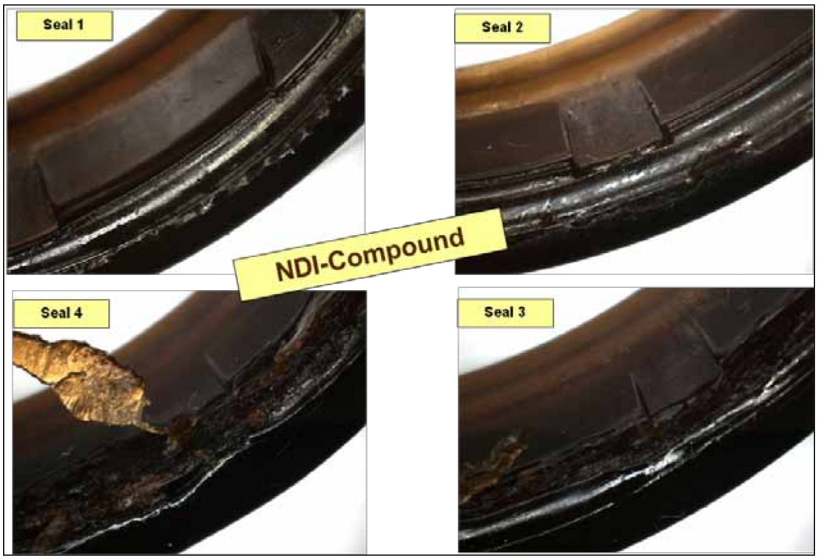


Figure 14—Details of thick extruded sections shown in Figure 13.

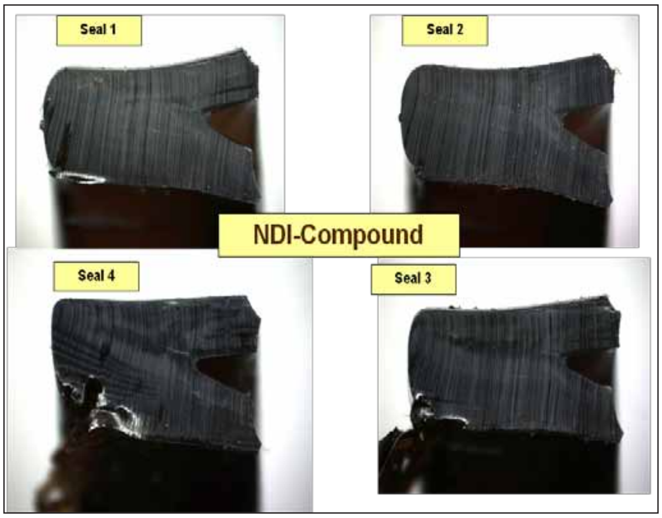


Figure 15—Cross-sections of seals from Figure 13; damage is especially evident.

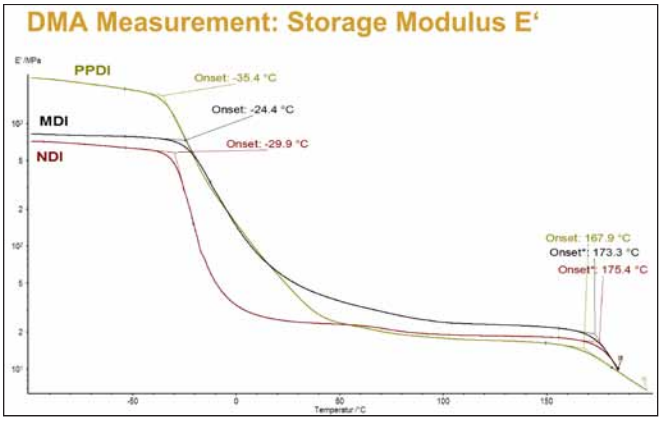
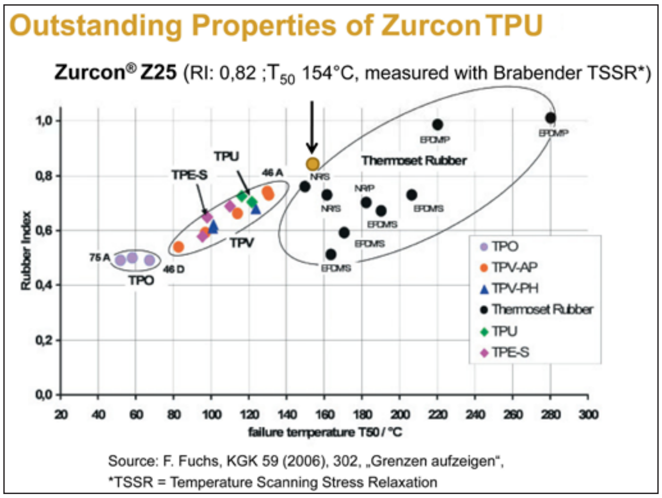


Figure 16—Comparison of change-of-interference of the four compounds after testing.



Source: F. Fuchs, KGK 59 (2006), 302, „Grenzen aufzeigen",
*TSSR = Temperature Scanning Stress Relaxation

Figure 17—Dynamic mechanical analysis (DMA) measurements comparing storage modulus (E′) of high-performance MDI material with NDI and PPDI materials.

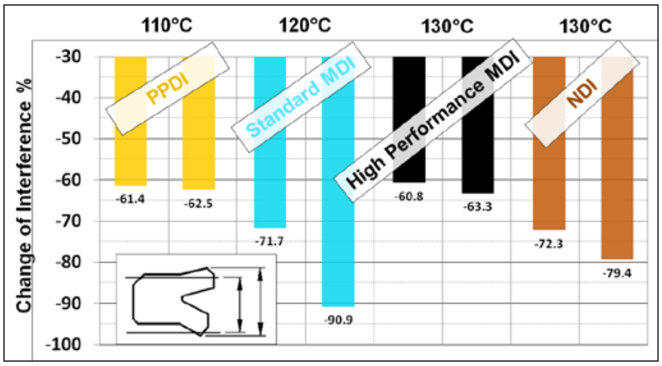
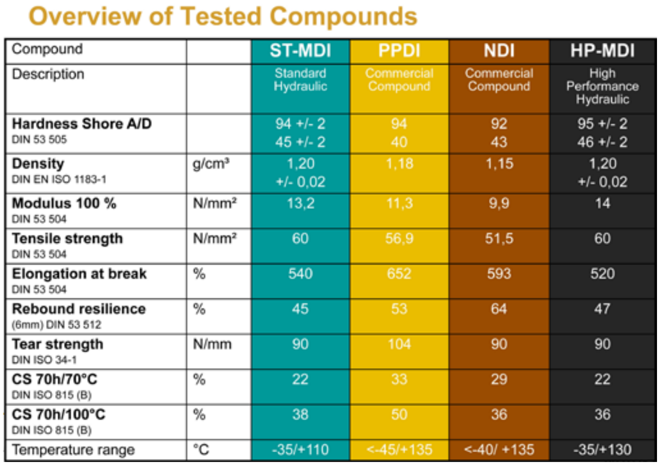


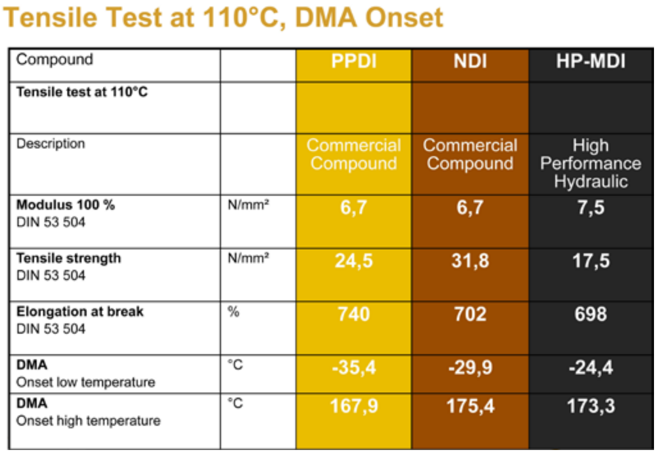
Figure 18—Comparison of TSSR results of traditional, commercial MDI-TPUs, thermoplastic elastomers (TPEs) and conventional thermoset rubber to the high-performance, MDI-based material.



Overview of Tested Compounds

Compound		ST-MDI	PPDI	NDI	HP-MDI
Description		Standard Hydraulic	Commercial Compound	Commercial Compound	High Performance Hydraulic
Hardness Shore A/D DIN 53 505		94 +/- 2 45 +/- 2	94 40	92 43	95 +/- 2 46 +/- 2
Density DIN EN ISO 1183-1	g/cm³	1,20 +/- 0,02	1,18	1,15	1,20 +/- 0,02
Modulus 100 % DIN 53 504	N/mm²	13,2	11,3	9,9	14
Tensile strength DIN 53 504	N/mm²	60	56,9	51,5	60
Elongation at break DIN 53 504	%	540	652	593	520
Rebound resilience (6mm) DIN 53 512	%	45	53	64	47
Tear strength DIN ISO 34-1	N/mm	90	104	90	90
CS 70h/70°C DIN ISO 815 (B)	%	22	33	29	22
CS 70h/100°C DIN ISO 815 (B)	%	38	50	36	36
Temperature range	°C	-35/+110	<-45/+135	<-40/ +135	-35/+130

Table 1—Overview of physical properties of tested materials



Tensile Test at 110°C, DMA Onset

Compound		PPDI	NDI	HP-MDI
Tensile test at 110°C				
Description		Commercial Compound	Commercial Compound	High Performance Hydraulic
Modulus 100 % DIN 53 504	N/mm²	6,7	6,7	7,5
Tensile strength DIN 53 504	N/mm²	24,5	31,8	17,5
Elongation at break DIN 53 504	%	740	702	698
DMA Onset low temperature	°C	-35,4	-29,9	-24,4
DMA Onset high temperature	°C	167,9	175,4	173,3

Table 2—Tensile test data at 110°C and onset temperature of DMA measurements