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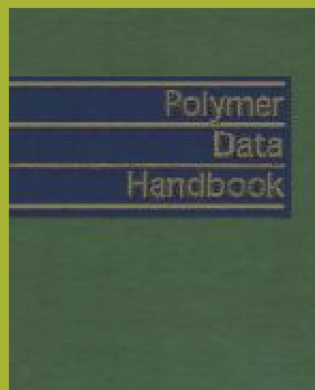
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POLYMER DATA HANDBOOK

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EDITED BY JAMES E. MARK, UNIVERSITY OF CINCINNATI

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The online version of the *Polymer Data Handbook* includes key data on over two hundred polymers. Please note that entries are presented as PDF files and can only be read using Adobe Acrobat Reader Version 3. If you do not have the freeware reader, it can be downloaded from [Adobe in the United States](#) or [Adobe in the United Kingdom](#). Each entry opens with a citation of the contributor's name and notations of acronyms and trade names, class of polymer, structure, and major applications. These are followed by tabular displays showing the properties of each polymer. The maximum consistency possible has been established for properties presented with regard to format, terminology, notations, and units. However, not all properties are applicable to all polymers contained in the handbook; some properties may not even be relevant for certain polymer classes. Also, some polymers exhibit properties shown by few others (e.g., electroluminescence); these properties have been noted as "Properties of Special Interest." Each entry closes with a list of references for the reader interested in further investigation of a polymer.

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Nylon 6

PAUL G. GALANTY

ACRONYM, ALTERNATIVE NAME, TRADE NAMES PA-6, poly- ϵ -caproamide, Capron[®], Ultramid[®], Nylatron[®]

CLASS Aliphatic polyamides

STRUCTURE $[-\text{NH}(\text{CH}_2)_5\text{CO}-]$

MAJOR APPLICATIONS Gears, fittings, and bearings. Electrical switches, bobbins, and connectors. Food packaging film. Monofilament for weed trimmers and fishing line. Blow and roto-molded containers. Wire and cable jacketing. Power tool housings, wheelchair wheels, automotive cooling fans, and other underhood parts.

PROPERTIES OF SPECIAL INTEREST Excellent load bearing (strength and stiffness) capability at elevated temperatures. Good chemical and abrasion resistance. Low coefficient of friction. Toughness and impact resistance.

PREPARATIVE TECHNIQUES (a) Hydrolytic polymerization of ϵ -caprolactam;⁽¹⁾ temperature = 250–260°C; pressure cycle for hydrolysis and addition; vacuum cycle for accelerated rate condensation. (b) Solid state polymerization for very high molecular weight;⁽¹⁾ temperature = 140–170°C (higher temperature causes discoloration); high vacuum to reach target molecular weight; nitrogen purge at atmospheric pressure is a costly alternative.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Monomer	—	—	ϵ -Caprolactam	(2)
Molecular mass	g mol^{-1}	—	113.16	
Melting point	K	—	342.2	
Boiling point	K	—	543	
Bulk density	g cm^{-3}	—	0.6–0.7	
Polymerization heats of reaction	kcal mol^{-1}	Hydrolysis Addition Condensation	2.1 –4 –6.1	(3)
Repeat unit	$[-\text{NH}(\text{CH}_2)_5\text{CO}-]$			(4)
Molecular mass range	g mol^{-1}	Typical as sold Solid state	$1.8\text{--}5.2 (\times 10^4)$ $\sim 1 \times 10^5$	(3)
Typical polydispersity index	—	—	1.9–2.0	(3)
IR (characteristic absorption frequencies)	cm^{-1}	Assignment N–H hydrogen-bonded stretch C=O amide I stretch C–N amide II stretch	3,300 1,640 1,545	(5)

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Chemical resistance⁽⁶⁾

Chemical	Temp. (°C)	Conc. (%)	Rating			
			Excellent	Good	Poor	Severe attack
Acetone	23	100	✓			
Benzene	23	100	✓			
Ethylene glycol/water	23	50		✓		
Ethylene glycol/water	120	50				✓
Formic acid	23	90				✓
Gasoline	100	100	✓			
Gasoline/methanol (15%)	23	15			✓	
Hydrochloric acid	23	10				✓
Potassium hydroxide	23	10		✓		
Potassium hydroxide	60	20			✓	
Trichloroethylene	23	100		✓		
Water	Up to 50	100		✓		
Water (steam)	100–150	100				✓

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Lattice	—	—	Monoclinic	(7)
Unit cell dimensions	nm	α structure	$a = 0.956, b = 1.724,$	(7)
		γ structure	$c = 0.801$ $a = 0.933, b = 1.688,$ $c = 0.478$	
Unit cell angles	Degrees	α structure	67.5	(7)
		γ structure	121	
Unit cell contents	—	α structure	4	(7)
		γ structure	4	
Heat of fusion	J g ⁻¹	Calorimetry	188	(8)
Density	g cm ⁻³	ASTM D-792; dry as molded	1.13	(9)
Degree of crystallinity	%	Typical molded	50	(10)
Mark-Houwink parameters: K and a	$K = \text{ml g}^{-1}$ $a = \text{None}$	In 85% formic acid; 25°C	$K = 0.023$ $a = 0.82$	(11)
Polymorphs	—	—	α, γ	(7)
Refractive index	—	At thickness < 0.5 mm; molded, undrawn	1.53	(12)
Glass transition temperature	K	DSC	320–330	(13)

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Melting point	K	ASTM D-789; Fisher-Johns	493	(9)
Specific heat	$\text{J g}^{-1} \text{K}^{-1}$	Neat, 0°C	1.38	(14)
		Neat, 120°C	2.30	
		Neat, 160°C	2.68	
Thermal expansion coefficient	mm (mm K)^{-1}	ASTM D-696		(9)
		Neat resin	8.30×10^{-4}	
		33% glass fiber	3.80×10^{-4}	
Deflection temperature under load	K	ASTM D-648		(9)
		Neat resin		
		Load = 1.80 MPa	338	
		Load = 0.45 MPa	438	
		33% glass fiber		
		Load = 1.80 MPa	483	
		Load = 0.45 MPa	493	
Tensile strength, yield	MPa	ASTM D-638		(9)
		Neat resin		
		DAM, 23°C*	79	
		DAM, 121°C	21	
		50% RH, 23°C*	36	
		33% glass fiber		
		DAM, 23°C	200	
		DAM, 121°C	83	
		50% RH, 23°C	127	
Tensile elongation, yield	%	ASTM D-638		(9)
		Neat resin		
		DAM, 23°C	7	
		DAM, 121°C	15	
		50% RH, 23°C	16	
		33% glass fiber		
		DAM, 23°C	3	
		DAM, 121°C	7	
		50% RH, 23°C	6	
Tensile elongation, ultimate	%	ASTM D-638		(9)
		Neat resin		
		DAM, 23°C	70	
		DAM, 121°C	>300	
		50% RH, 23°C	260	
		33% glass fiber		
		DAM, 23°C	3	
		DAM, 121°C	7	
		50% RH, 23°C	6	

Nylon 6				
PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Flexural strength	MPa	ASTM D-790		(9)
		Neat resin		
		DAM, 23°C	108	
		DAM, 121°C	17	
		50% RH, 23°C	35	
		33% glass fiber		
		DAM, 23°C	276	
Flexural modulus	MPa	DAM, 121°C	112	(9)
		50% RH, 23°C	179	
		ASTM D-790		
		Neat resin		
		DAM, 23°C	2,829	
		DAM, 121°C	304	
		50% RH, 23°C	738	
Notched Izod impact strength	J m ⁻¹	33% glass fiber		(9)
		DAM, 23°C	9,384	
		DAM, 121°C	3,319	
		50% RH, 23°C	5,127	
		ASTM D-256		
		Neat resin		
		DAM, 23°C	53	
Hardness, Rockwell	R scale	50% RH, 23°C	NB	(9)
		33% glass fiber		
		DAM, 23°C	117	
Abrasion resistance	mg kcycles ⁻¹	50% RH, 23°C	235	(15)
		ASTM D-785; DAM, 23°C		
		Neat resin	119	
Volume resistivity	ohm cm	33% glass fiber	121	(9)
		ASTM D-1044, Taber; DAM, 23°C		
		Neat resin	9	
Surface resistivity	ohms	33% glass fiber	30	(9)
		ASTM D-257; DAM, 23°C		
		Neat resin	1.00 × 10 ¹⁴	
Dielectric constant	—	33% glass fiber	1.00 × 10 ¹⁵	(9)
		ASTM D-257; DAM, 23°C		
		Neat resin	1.00 × 10 ¹⁵	
Dissipation factor	—	33% glass fiber	1.00 × 10 ¹⁵	(9)
		ASTM D-150; DAM, 23°C, 1 MHz;		
		33% glass fiber	3.80	
Dissipation factor	—	ASTM D-150; DAM, 23°C, 1 MHz;		(9)
		33% glass fiber	0.022	
		33% glass fiber		

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Dielectric strength, short time	kV mm ⁻¹	ASTM D-149; DAM, 23°C, 3.2 mm		(9)
		Neat resin	460	
		33% glass fiber	560	
Thermal conductivity	W (m K) ⁻¹	—	0.23	(16)
Coefficient of friction	—	ASTM D-1894, polymer to steel		(17)
		Neat resin		
		Static	0.24	
		Dynamic	0.16	
		33% glass fiber		
		Static	0.25	
Thermal index ratings	K	UL-746B; 60,000-h half-life at indicated temperature; 3.2 mm		(9)
		Neat resin		
		Mechanical	378	
		Impact	378	
		Electrical	403	
		33% glass fiber		
		Mechanical	413	
		Impact	393	
		Electrical	413	
Moisture absorption	%	ASTM D-570; 23°C		(9)
		Neat resin		
		50% RH equilibrium	2.7	
		Saturation	9.5	
		33% glass fiber		
		50% RH equilibrium	1.9	
Flammability ratings		UL-94; 3.2 mm		(9)
		Neat resin	V-2	
		33% glass fiber	HB	
Price	US\$ kg ⁻¹	Commercial quantities of 2–5 (×10 ⁵) kg yr ⁻¹		(18)
		Neat resin	0.66–0.68	
		33% glass fiber	0.68–0.70	
Major suppliers	AlliedSignal, Morristown, New Jersey BASF, Mt. Olive, New Jersey Bayer, Pittsburgh, Pennsylvania Custom Resins, Henderson, Kentucky DuPont, Wilmington, Delaware Nylatech, Manchester, New Hampshire			

*DAM = tested dry as molded; 50% RH = tested after equilibration in a 50% RH, 23°C room.

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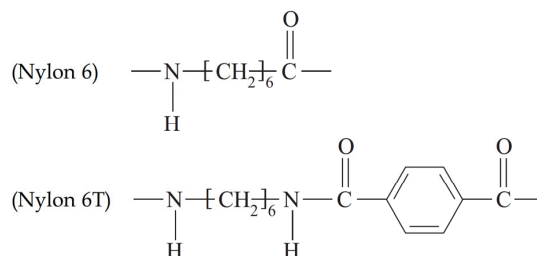
Nylon 6 copolymer

SHAW LING HSU

TRADE NAME, ALTERNATIVE NAMES Ultramid T (BASF), nylon 6/6T, polyphthalamide

CLASS Aromatic polyamides; aromatic nylon

STRUCTURE These aromatic nylons consist of aliphatic and aromatic building blocks incorporating the repeat units of nylon 6—poly(caprolactam)—and nylon 6T—poly(hexamethylene terephthalamide). Because of this composition, Ultramid T resins are often designated as nylon 6/6T materials. The basic structure is nylon 6/6T, with a majority component of nylon 6.



PROPERTIES OF SPECIAL INTEREST Extremely high melting temperature can be achieved by adjusting the relative amount of the aromatic component. Good mechanical properties at elevated temperatures. Good resistance to chemicals. Good dielectric properties. Dimensional stability in the presence of moisture. Low moisture absorption, good impact resistance, good dielectric properties, good resistance to chemicals, easy to process.

MAJOR APPLICATIONS High-temperature applications, automobile parts (e.g., radiator, ventilation, and fuel supply systems), electronics housings, plug and socket connectors, printed circuit boards, tennis rackets, golf clubs.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
NMR*	ppm	Range for amide proton peaks Range for methylene proton peaks	6–7 1–4	(1)
IR (characteristic absorption frequencies)	cm ⁻¹	Overall, the infrared spectrum greatly resembles those found for other polyamides. The principal spectroscopic features can be definitively assigned. N–H stretching Amide I Amide II Range for symmetric and asymmetric methylene stretching vibrations Methylene bending vibrations	 3,305 1,627 1,545 3,000 1,400	 (2, 10) (2, 10) (2, 10) (3–7, 9–15) —

Nylon 6 copolymer				
PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
IR (characteristic absorption frequencies)	cm ⁻¹	Other specific spectroscopic features can be linked to the presence of the nylon 6T component Vibrations assignable to para-disubstituted aromatic units	862, 1,019, ~1,300, [†] 1,498	(16, 17) (3, 8, 18)
Melting temperature [‡]	K	—	583–613	(20, 21)
Glass transition temperature	K	—	473	(21)
Degradation of aromatic polyamides		Plasma treatment can modify aromatic nylons reducing the concentration of amide units relative to that in untreated nylon 6,6 copolymer. When these polyamides are dissolved in acidic solution, the polyamic is gradually degraded.		(22)
Density	g cm ⁻³	—	1.18	(20)
Linear thermal expansion coefficient	%	60°C	0.2	(20)
Tensile modulus	MPa	Dry and moist	3,200	(20)
Tensile strength	MPa	Dry Moist	100 90	(20)
Heat deflection temperature	K	At 624 psi	473	(20)
Dielectric constant	—	1 MHz	4.0	(20)
Moisture absorption	%	23°C, saturation 23°C, 50% RH	7 1.8	(21) (20)
Solvents		Hexafluoroisopropanol (HFIP)		(22)

^{*}Both assignments fall into the range of peak positions listed for these groups in standard NMR tables.

[†]Broad features

[‡]A broad melting behavior starts at approximately 483 K and ends at approximately 563 K. These trends are consistent with the melting behaviors reported for nylon 6/6T copolymers.⁽¹⁹⁾

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Polyethylene, low-density

A. PRASAD

ACRONYMS LDPE, branched PE, high-pressure PE

CLASS Poly(α -olefin)

STRUCTURE $-\text{[CH}_2-\text{CH}_2\text{]}_n-$

INTRODUCTION LDPE is produced under high pressure (82–276 MPa) and high temperature (405–605 K) with a free radical initiator (such as peroxides and oxygen) and contains some long chain branches (LCB), which could be as long as chain backbones,^(1,2) and short chain branches (SCB).⁽³⁾ It is produced by either a tubular or a stirred autoclave reactor.⁽⁴⁾ The autoclave process can produce LDPE resins having a wide range of molecular weight distribution (MWD) and less LCB in comparison with a tubular reactor.⁽⁴⁾ Long chain branching has a strong influence on MWD, and hence on resin properties, such as processibility, melt strength, and film optical properties.⁽⁴⁾ SCBs disrupt chain packing and are principally responsible for lowering the melting temperature and the crystal density for hydrocarbon polymers. LDPE is commercially available in a wide variety of molecular weight, MWD, SCB, and LCB contents, and density ranges.^(4–6)

Thermal and mechanical properties of semicrystalline polymers are strongly dependent on MW, MWD, branching content, and density.^(5, 7, 8) Controlled variations in these structural parameters result in a broad family of products with wide differences in thermal and mechanical properties. Shear modified LDPE samples are also available commercially.^(9,10) The deliberate shearing of polymer melt results in a reduction in melt viscosity and elasticity without significant change in MW.⁽¹¹⁾ These reversible changes are advantageous for molding and extrusion and also result in film with better optical properties.^(9,10,12) Shear modified LDPEs show vastly different crystallization rates.⁽¹²⁾ The properties shown in the following table are given in ranges because of their dependence on molecular structure and are intended to represent best published examples of most commonly used commercial grades of LDPE for blown film, molding, and extrusion coating applications. Table 3 contains properties of tubular blown films.

MAJOR APPLICATIONS Major applications include blown film for bags and packaging; extrusion coatings for paper, metal, and glass; and injection molding for can lids, toys, and pails. Other applications include blow molding (squeeze bottles), rotomolding and wire and cable coatings, carpet backing, and foam for packaging material. There is considerable use of blends of LDPE with high-density polyethylene (HDPE) and linear low-density polyethylene (LLDPE) in a wide variety of applications. These blends are deliberately excluded in the data presented below.

PROPERTIES OF SPECIAL INTEREST LDPE has a good balance of mechanical and optical properties with easy processibility and low cost. It can be fabricated by many different methods for a broad range of applications. Special properties of interest include: optical clarity, flexibility, toughness, high impact strength, good heat seal, low brittleness temperature, good chemical resistance to aqueous solvents, and good electrical properties. LDPE may not be suitable for applications that require

Polyethylene, low-density

high stiffness and high tensile strength. Other limitations include: poor resistance to oxidizing agents, aliphatic solvents, aromatic solvents, polar liquids, chlorinated solvents, low softening point, poor scratch resistance, poor gas and moisture permeability, and relatively lower stress-crack resistance when compared to other types of polyethylene. LDPE undergoes thermal degradation at high temperatures and chain extension under shear conditions.

MAJOR SUPPLIERS Equistar Chemicals LP., Dow Chemical Co., Chevron Chemical Co., Westlake Plastics Co., Du Pont Co., Exxon Chemical Co., Eastman Chemical Co., Union Carbide Corp., Mobil Polymers, Rexene Corp., Novacor Chemicals, Inc.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Type of branching	—	FTIR, NMR	Methyl, ethyl, butyl, amyl and longer branches	(13-15)
Type of unsaturation	%	FTIR		(16)
		Vinylidene	80	
		Vinyl	10	
		<i>Trans</i>	10	
Degree of SCE, commercial grades	Methyl/1,000 carbon	FTIR, NMR	10-33	(13-15)
Typical M_w range, commercial grades	g mol^{-1}	GPC	$3-40 \times 10^4$	(5, 16)
Typical polydispersity index (M_w/M_n)	—	GPC, strongly influenced by the amount of LCB	4-30	(17-19)
IR (characteristic absorption frequencies)	cm^{-1}	Thin film sample at room temperature	See table below	(14, 15, 20)

Characteristic frequencies of crystalline LDPE*

Wave number	Intensity	Assignments
720	Very strong	CH ₂ rocking
731	Very strong	CH ₂ rocking
888	Very weak	Vinylidene groups
890	Very weak	CH ₃ rocking
908	Medium	Terminal vinyl groups
964	Very weak	<i>Trans</i> double bond
990	Weak	Terminal vinyl groups
1,050	Very weak	CH ₂ twisting
1,176	Very weak	CH ₂ wagging
1,375	Weak-medium	CH ₃ symmetrical bending
1,457	Very weak	CH ₃ asymmetrical bending
1,463	Very strong	CH ₂ bending

Polyethylene, low-density

Characteristic frequencies of crystalline LDPE*

Wave number	Intensity	Assignments
1,473	Very strong	CH ₂ bending
2,850	Very strong	CH ₂ symmetrical stretching
2,857	Very strong	CH ₂ symmetrical stretching
2,874	Weak	CH ₃ symmetrical stretching
2,899	Very strong	CH ₂ asymmetrical stretching
2,924	Very strong	CH ₂ asymmetrical stretching
2,960	Weak	CH ₃ asymmetrical stretching

*Observed in the infrared spectra and band assignments.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Linear thermal expansion coefficient	K ⁻¹ (×10 ⁻⁵)	D 696 Temperature range = 238–423 K	10.0–51.0 See table below	(21–23) (5, 16)

Temp. (K)	Coefficient of expansion (×10 ⁻⁵)	
	Linear	Cubical
238	10.0	30.0
273	18.3	55.0
293	23.7	71.0
313	29.0	87.0
333	33.7	101.0
353	40.3	121.0
373	46.6	140.0
383	51.0	153.0
388–423	25.0	75.0

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Density (amorphous)	g cm ⁻³	At 298 K, extrapolated from melt temperature	0.855	(24, 25)
Solvents	—	368 K 369 K 371 K 341 K 374 K	Decalin, toluene Xylene Tetralin Cyclohexene <i>n</i> -Tetracosane	(26, 27)
Nonsolvents	—	359 K 361 K 366 K	Methylene chloride <i>o</i> -Dichloro benzene 1,2-Dichloropropane	(27)

Polyethylene, low-density				
PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Solubility parameter	(MPa) ^{1/2}	<i>n</i> -Tetracosane, 374 K	15.20	(27)
		Cyclohexene, 341 K	17.10	(27)
		<i>n</i> -Heptane, 359 K	14.57	(27)
		<i>n</i> -Octane, 361 K	14.50	(27)
		<i>n</i> -Hexane, 359 K	12.46	(27)
		<i>n</i> -Pentane, 361 K	12.52	(27)
		Chloroform, 350 K	16.00	(27)
		Carbon tetrachloride, 346 K	14.77	(27)
		Tetrachloroethylene, 346 K	15.69	(27)
		Chlorobenzene, 349 K	18.13	(27)
		<i>o</i> -Dichlorobenzene, 361 K	18.62	(27)
		Methylene chloride, 359 K	13.75	(27)
		See also the other references for more data	—	(27, 28–31)
Theta temperature θ	K	Bis(2-ethylhexyl)adipate	418–443	(28)
		Bis(2-ethylhexyl)sebacate	423	
Flory interaction parameter χ	—	<i>n</i> -Tetracosane, 374 K	–0.09	(27)
		Cyclohexene, 341 K	–0.03	(27)
		<i>n</i> -Heptane, 359 K	0.13	(27)
		<i>n</i> -Octane, 361 K	0.18	(27)
		<i>n</i> -Octane, 393 K	0.31	(29)
		<i>n</i> -Octane, 418 K	0.30	(29)
		<i>n</i> -Hexane, 359 K	0.23	(27)
		<i>n</i> -Pentane, 361 K	0.35	(27)
		Toluene, 393 K	0.34	(29)
		Xylene, 350 K	0.51	(29)
		<i>m</i> -Xylene, 393 K	0.29	(29)
		<i>p</i> -Xylene, 393 K	0.27	(29)
		Chloroform, 350 K	0.25	(27)
		Tetrachloroethylene, 346 K	–0.05	(27)
		Chlorobenzene, 349 K	0.04	(27)
		<i>o</i> -Dichlorobenzene, 361 K	0.41	(27)
		Methylene chloride, 359 K	0.60	(27)
		Carbon tetrachloride, 346 K	0.01	(27)
		See also the other references for more data	—	(27–29)
Second virial coefficient A_2	mol cm ³ g ^{–2}	Tetralin, 334 K		(32, 33)
		$M_w = 5.73 \times 10^5$	0.92×10^{-4}	
		$M_w = 1.98 \times 10^6$	0.84×10^{-4}	

Polyethylene, low-density

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Mark-Houwink parameters: K and a	$K = \text{ml g}^{-1}$ $a = \text{None}$	Should be used for approximate MW values only because LDPE contains long-chain branching Decalin, 342 K p -Xylene, 347 K Xylene, 353 K	— $K = 3.87 \times 10^{-4}$, $a = 0.78$ $K = 1.05 \times 10^{-3}$, $a = 0.63$ $K = 1.35 \times 10^{-4}$, $a = 0.63$	(32–36) (36) (33) (34)
Characteristics ratio $\langle r^2 \rangle / nl^2$	—	Tetralin, 334 K	7.26, 7.58	(32)
Crystallographic data	Å	Wide-angle X-ray (WAXD)	See table below	(37–40)

Unit cell information

Lattice	Space group	Unit cell dimensions (Å)			Monomers per unit cell	Reference
		a	b	c		
Orthorhombic	Pnam	7.40	4.93	2.534	2	(37)
		7.36	4.92	—	—	(38)
		7.51	4.97	—	—	(39)
Monoclinic	C2/m	8.09	2.53	4.79	2	(40)

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Crystallinity	%	DSC	33–53	(41–48)
Heat of fusion (per repeat unit)	kJ mol^{-1}	DSC	1.37–2.18	(41–48)
Density	g cm^{-3}	Commercial resins, ASTM D 1505	0.910–0.935	(4–6)
		Unit cell, 100% crystalline	1.00	(37)
		Unit cell, 100% crystalline	1.014	(38)
Lamellae thickness	Å	Raman longitudinal acoustic mode (LAM), various crystallization conditions used	See Table 1	(16, 48)
Crystal phase structure	%	LAM	See Table 1	(48)
Crystal orientation and birefringence	—	WAXD and infrared diachroism	See Table 2	(58)
Melting temperature	K	DSC, peak endotherms	378–388	(5, 6, 41, 44)

Polyethylene, low-density

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Glass transition temperature	K	DMA, TMA	140–170 (See also transition and relaxation temperature table below)	(45–47)
Transition and relaxation temperatures; and activation energy*	—	DMA	See table below	(16, 45–49)

*The transitions and relaxation temperatures associated with amorphous regions are designated as α , β , γ , etc. in descending temperature order. Several conflicting interpretations and values have been given regarding the origin and molecular nature of the transitions in LDPE (see references 45 to 49). It is believed that the values of T_a depends on crystallite thickness. The temperature of beta transition, T_β , does not depend on the crystallite thickness but rather the comonomer type and content. The γ transition is associated with glass transition. All transition values depend on the frequency of the DMA test. See references (46) and (47) for detailed discussions. The transition temperatures associated with peaks in dynamic loss listed in this table are given in ranges because of a wide range of values cited in the literature (for a specific examples see Table 1 below).

Transitions	Temperature range (K)	Approximate activation energy (kJ mol ⁻¹)
α	293–360	>420
β	233–280	160–200
γ	140–170	32–75

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Heat capacity (of repeat units)	kJ k ⁻¹ mol ⁻¹	At constant pressure and temperature of 298 K, (density = 0.921 g cm ⁻³) At other temperatures	1.6536 × 10 ⁻⁴ —	(50, 51) (51)
Enthalpy (of repeat unit)	kJ mol ⁻¹	Calorimeter Temperature (K) 80 140 200 260 320 380 415	0.287 0.883 1.722 2.887 4.545 7.619 9.384	(51)
Entropy (of repeat unit)	kJ k ⁻¹ mol ⁻¹	Calorimeter Temperature (K) 80 140 200 260 320 380 415	0.00586 0.0114 0.0164 0.0214 0.0273 0.0357 0.0406	(51)

Polyethylene, low-density

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Deflection temperature	K	D 648, at 273 K and 0.45 MPa	311–322	(23)
Heat distortion temperature	K	D 648, 455 KPa	313–323	(21)
Vicant softening point	K	D 1525	363–375	(5)
Tensile modulus	MPa	D 638	102–310	(5, 21, 52)
Compressive strength	MPa	D 695	18–25	(23)
Tensile yield strength	MPa	D 638	9–15	(5, 21, 52)
Elongation at break	%	D 638	100–800	(5, 21, 52)
Yield stress	MPa	D 638	6.2–11.5	(5, 21, 52)
Flexural modulus	MPa	D 790 at 298 K	240–330	(6, 21, 52)
Impact strength, notched Izod	J m ⁻¹	D 256A	No break	(6, 21, 52)
Hardness	Shore D	D 676	40–60	(5, 6, 21, 52)
Low-temperature brittleness F ₅₀	K	D 746	<197	(21, 52)
Refractive index	—	D 542, crystalline (value depends on density and chain branching)	1.5168–1.5260	(21, 53)
		Amorphous	1.49	(16, 54)
		Refractive index in melt	See table below	(54)
Specific volume	cm ³ g ⁻¹	Differential refractometer and dilatometer, Alathon 10	See table below	(54)
Specific refractivity	cm ³ g ⁻¹	Differential refractometer and dilatometer, Alathon 10	See table below	(54)

Temperature (K)	Specific volume (cm ³ g ⁻¹)	Refractive index	Refractivity (cm ³ g ⁻¹)
363.16	1.159	1.4801	0.3293
368.16	1.168	1.4736	0.3281
373.16	1.178	1.4693	0.3283
378.16	1.195	1.4630	0.3291
381.16	1.209	1.4575	0.3297
384.16	1.282	1.4510	0.3290
386.16	1.239	1.4432	0.3286
391.16	1.250	1.4392	0.3289
387.56	1.256	1.4368	0.3288

Polyethylene, low-density				
PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Dielectric constant ϵ'	—	D 150 at 1kHz Density (g cm^{-3}) 0.920 0.930 0.935	2.28 2.30 2.31	(5, 21, 55)
Loss factor, $\tan \delta$	—	Up to 100MHz	10^{-4} – 10^{-3}	(5, 21)
Dielectric strength	Mv cm^{-1}	D 149, 283 K D 149, 373 K	7.0 2.0	(21, 55, 56)
Power factor	—	D 150 at 1kHz	0.0003	(5)
Melt index	g (10 min)^{-1}	D 1238	0.2–50	(4, 6)
Flow activation energy: EH and E_V^*	kJ mol^{-1}	RMS, mel: index = $\sim 1 \text{ g (10 min)}^{-1}$ density = $0.919\text{--}0.931 \text{ g cm}^{-3}$, temp. range = 423–483 K	$E_H = 61\text{--}67$ $E_V = 8\text{--}10.5$	(59)
Coefficient of sliding friction μ	—	D 1894, dynamic c.o.f. to stainless steel, melt index = $2 \text{ g (10 min)}^{-1}$ density = 0.915 g cm^{-3}	0.7	(57)
Sonic velocity	m s^{-1}	Blown films	See Table 2	(58)
Water absorption	%	D 570, 24 h	<0.02	(21)

*The horizontal shift factor reflects the temperature dependence of relaxation time, and the vertical shift factor reflects the temperature dependence of modulus.

Table 1. Morphological and relaxation properties of LDPE as a function of crystallization condition^{*(48)}

Condition	α -Relaxation	β -Relaxation	Crystallinity (%)	Crystallite thickness (Å)	% Crystal phase structure		
	(K, 3.5 Hz)	(K, 3.5 Hz)			α_c	α_a	α_b
Slow cooled	348	258	36	105	37	49	14
Cooled in air	323	258	—	82	—	—	—
Quenched 30°C	323	258	40	80	36	53	11
Quenched 40°C	278	—	—	70	—	—	—
Quenched 0°C	273	—	32	—	—	—	—
Quenched –120°C	270	—	29	65	38	49	13

* $M_w = 3.46 \times 10^5$, $M_w/M_n = 18.5$, total SCB/1,000 C = 10.5, LCB/1,000 C = 2.2.

Note: Compression molded specimens were rapidly quenched to the specified quenching temperatures. Relaxation temperatures ($\tan \delta$ peaks) were obtained on a DMA instrument at a heating scan rate of 1°C min^{-1} . Crystal phase structures were obtained by Raman LAM. The degree of crystallinity was determined from the heat of fusion data obtained on a DSC instrument.

Polyethylene, low-density

Table 2. Morphological properties and crystal orientation of LDPE (density 0.920 g cm⁻³) blown tubular films⁽⁵⁸⁾

Thickness (μm)	Density (g cm ⁻³)	Birefringence (×10 ³)	Sonic velocity (ms ⁻¹)		Infrared diachroic ratio (at 730 cm ⁻¹)	X-ray angle (degree)			
			MD ⁺	TD ⁺		a-axis		b-axis	
						MD-TD ⁺	ND-MD ⁺	MD-TD ⁺	ND-MD ⁺
54	0.9182	-9.79	953	1,128	1.15	45-50	45-60	0	0
26	—	-8.23	870	1,003	0.88	45	45-60	0	0
23	0.9175	-3.07	852	998	1.13	70	60-70	0	0

*MD, TD, and ND refers to the machine, transverse, and normal direction of a blown film sample.

Table 3. Blown film properties of high clarity grade LDPE*

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Melt index	g (10 min) ⁻¹	D 1238	2.0	(66)
Density	g cm ⁻³	D 1505	0.924	(66)
Peak melting point	K	DSC, 10°C min ⁻¹ cooling and heating rate	382.5	(66)
Heat of fusion	kJ mol ⁻¹	DSC, 10°C min ⁻¹ cooling and heating rate	1.50	(66)
M _w	g mol ⁻¹	GPC, 408 K in 1,2,4-trichlorobenzene	79,200	(66)
M _w /M _n	—	GPC	3.8	(66)
Total haze	%	D 1003	5.2	(66)
Gloss, 45°D	Units	D 2457	71	(66)
Narrow angle scattering	%	D 1746	72	(66)
Modulus, 1% secant	MPa	D 882, MD D 882, TD	200 240	(66)
Dart impact (per mil)	g	D 1709, D 4272	74	(66)
Elmendorf tear	g	D 1922, MD D 1922, TD	360 220	(65)
Tensile strength at break	MPa	D 882, MD D 882, TD	25 17	(66)
Elongation at break	%	D 882, MD D 882, TD	290 500	(66)

*Film and optics properties depend upon processing conditions (see references 9, 10, 60-65). This table presents some representative values of typical high clarity grade LDPE films processed using the following conditions: blow-up ratio = 2:1; die gap = 0.635 mm; output = 48 kg h⁻¹; film thickness = 30.5 μm; die = 203 mm; frost line height = 330 mm; melt temperature = 463 K.

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Polypropylene, isotactic

DAVID V. HOWE

ACRONYM PP

CLASS Poly(α -olefins)

STRUCTURE

$$\begin{array}{c} \text{CH}_3 \\ | \\ [-\text{CH}_2\text{CH}-] \end{array}$$

MAJOR APPLICATIONS Fiber, slit tape, cast and biaxially oriented film, containers and closures, automotive interior trim, appliance housings and components, component in elastomeric blends with polyethylene and olefinic rubbers.

PROPERTIES OF SPECIAL INTEREST Low cost; easily processed by injection molding, extrusion, and spinning; can be oriented; excellent resistance to chemicals; low color; can be stabilized to provide good thermal aging stability; moderate strength and stiffness; good toughness when impact modified either in the reactor or by compounding; excellent flexural fatigue resistance; modest clarity.

PREPARATIVE TECHNIQUES Ziegler-Natta polymerization with titanium halide/aluminum alkyl catalyst and, optionally, ether, ester, or silane activator. Catalyst may be deposited on a magnesium chloride support. Slurry and gas phase processes are used. Catalyst systems based on metallocenes are under development. Typical comonomers are ethylene and 1-butene.

Isotacticity

Polymerization Conditions	Isotacticity				Reference
	Isotactic index (% heptane insolubles)	Xylene insolubles	% mmmm	% mm	
MgCl ₂ /TiCl ₄ /DIBP* catalyst modified with TMPIP* and AlEt ₃ prepared at 140°C	—	94	89.3	—	(1)
MgCl ₂ /TiCl ₄ /DIBP* catalyst modified with (<i>i</i> -Bu) ₂ Si(OMe) ₂ and AlEt ₃	97	—	—	—	(2)
MgCl ₂ /TiCl ₄ /DE* catalyst modified with AlEt ₃	95–99	—	—	—	(3)
Various MgCl ₂ or TiCl ₃ supported Ziegler-Natta catalysts	—	—	—	92.2–94.9	(4)

*DIBP = Diisobutyl phthalate; TMPIP = 2,2,6,6-tetramethylpiperidine; DE = 1,3-diether.

Polypropylene, isotactic

Molecular weight (M_w) and polydispersity index (M_w/M_n)

Polymerization conditions	M_w (g mol ⁻¹)	M_w/M_n	Reference
MgCl ₂ /TiCl ₄ /DIBP catalyst modified with (<i>i</i> -Bu) ₂ Si(OMe) ₂ and AlEt ₃			(2)
I ₂ concentration = 0 mol l ⁻¹	560,000	3.8	
H ₂ concentration = 6.9×10^{-3} mol l ⁻¹	382,000	6.1	
Typical range (extrapolated from melt flow rates of commercial products)	<100,000–>600,000	5–12	(5, 6)
Borealis VC20 82C (MFR: 20 g/10 min)	265,000	4.3	(7)
Typical for controlled rheology (chemically cracked products)	—	<5	(8, 9)
Single site catalyst	—	~2	(10)
Melt flow index			(5)
0.63	646,000	—	
2.9	412,000	—	
11.9	297,000	—	

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Molecular weight of repeat unit	g mol ⁻¹	—CH ₂ —CH(CH ₃)—	42.07	
Morphology (blends, 'impact copolymer')	—	Elastomer content <~60% Elastomer content >~60% (depends upon processing conditions)	Dispersed phase Dispersed or co-continuous phase	(11)
IR (characteristic absorption frequencies)	cm ⁻¹	CH ₃ , CH ₂ , CH stretching CH ₃ antisymmetric bending, CH ₂ bending Various CH ₃ , CH ₂ , and CH bending, wagging, twisting, C—C stretching Various CH ₃ , CH ₂ , and CH bending, wagging, twisting, and rocking, C—C stretching	2956 (s), 2951 (s), 2925 (sh), 2907 (sh), 2880 (s), 2868 (s), 2843 (s) 1459 (sh), 1454 (s) 1377 (s), 1359 (m), 1329 (w), 1305 (w), 1297 (w), 1257 (w), 1219 (w) 1167 (s), 1153 (sh), 997 (s), 973 (s), 841 (s), 809 (m)	(12, 13)
NMR		¹ H NMR ¹³ C NMR		(14–17) (18, 19)
Coefficient of linear thermal expansion	K ⁻¹	ASTM Method D696 From 243 to 273 K From 273 to 303 K From 303 to 330 K	6.5×10^{-5} 1.05×10^{-4} 1.40×10^{-4}	(20)

Polypropylene, isotactic

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Coefficient of thermal expansion (volume, melt)	K ⁻¹	From 448 to 573 K	6.6×10^{-4}	(21)
		From 453 to 503 K	6.7×10^{-4}	(22)
Isothermal compressibility	bar ⁻¹	453 K	1.27×10^{-4}	(22, 23)
		493 K	1.5×10^{-4}	
		533 K	1.78×10^{-4}	
Density	g cm ⁻³	298 K, α -crystalline phase	0.936–0.946	(24, 25, 26)
		298 K, amorphous phase	0.850–0.855	
		298 K, typical commercial material	0.90–0.91	
Solvents		Room temperature	No common solvents	(27)
Solubility parameter	(MPa) ^{1/2}	Inverse phase gas chromatography	18.8	(28)
		Montell Profax 6701	17.3	(29)
Theta temperature	K	$M_w = 28,000$ – $564,000$		(30, 31)
		<i>p</i> -tert-amylphenol	414	
		dibenzyl ether	456	
		biphenyl	398	
Lattice	—	α_1 , α_2 -forms	Monoclinic	(24, 32)
		β -form	Hexagonal	(32)
		γ -form	Orthorhombic	(32, 33, 34)

Form	Space group	Chain conformation	Unit cell dimension (Å)			Unit cell angle (degrees)	Conditions	Reference
			a	b	c			
α_1	C ₁ /c	Helix (3/1)	6.67	20.8	6.50	98.67	Oriented, annealed 413 K	(35)
α_2	P2 ₁ /c	Helix (3/1)	6.65	20.73	6.50	98.67	Oriented, annealed 443 K	(35)
β	P3 ₁ 21	Helix (3/1)	11.03	11.03	6.49	—	—	(32)
γ	Fddd	Helix (3/1)	8.54	9.93	42.41	—	—	(32, 33, 34)

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Heat of fusion	J g ⁻¹	DSC, α -crystalline material (100%)	165	(25)
Degree of crystallinity	%	DSC, density depends upon tacticity and crystallization conditions	50–70	(4, 7, 26)
Glass transition temperature	K	DMA		(7)
		30 Hz	283.7	
		1 Hz	275.5	
Melting point	K	100% crystalline	~459	(36)

Polypropylene, isotactic

Commonly reported mechanical properties*

PROPERTY	UNITS	CONDITIONS	POLYMER TYPE			
			IPP ^(a)	RCP ^(b)	IPC-L ^(c)	IPC-H ^(c)
Yield stress	MPa	ASTM D638	34.5	27.6	26.2	22.0
Yield strain $(L/L_0)_y$	%	ASTM D638	10	14	12	14
Flexural modulus	MPa	ASTM D790	1,389	1,035	1,210	1,000
Izod impact strength ^(d)	J m ⁻¹	ASTM D256	27	55	130	No break
Hardness	Rockwell	ASTM D785	R90	R80	R80	R60
Deflection temperature	K	ASTM D648, 0.45 MPa outer fiber stress	380	360	360	345

* These are typical properties for the classes of materials based on the range of properties reported in references (37) and (38).

^(a) IPP = isotactic propylene homopolymer.

^(b) RCP = ethylene-propylene random copolymer with an ethylene content of about 3%.

^(c) IPC = blends of isotactic propylene homopolymer with ethylene-propylene rubber. These materials are commonly called "impact copolymers," "heterophasic copolymers," or, incorrectly, "block copolymers." These are typically prepared during the polymerization process using a series of reactors. L = low rubber (less than about 15% rubber by weight; typically with an ethylene content of less than about 10%). H = high rubber content blends (greater than about 15% rubber by weight; typically with an ethylene content of at least 7%).

^(d) Impact strength is very dependent upon the molecular weight of the polymer as well as the rubber content of the material. These data are for typical injection molding grade materials.

PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Storage modulus	MPa	293 K, Homopolymer, 30 Hz	1,400	(7)
Tan δ	—	293 K, Homopolymer, 30 Hz	0.086	(7)
Poisson ratio	—	296 K	0.38	—
Index of refraction n_D	—	293 K, density 0.9075 g cm ⁻³	1.5030	(39)
Refractive index Increment dn/dc	—	1-Chloronaphthalene and 1,2,4-trichlorobenzene solvents	(see reference)	(40)
Dielectric constant ϵ'	—	At 1 KHz (D150)	2.2-2.3	(26)
		At 1 MHz	2.1-2.3	(41)
Dielectric strength	V cm ⁻¹	298 K (D149)	240,000	(26)
		298 K	217,000-300,000	(41)
		393 K	170,000	(26)
Dissipation factor	—	60 Hz-100 MHz (D510)	0.3-1 ($\times 10^{-3}$)	(26)
		1 MHz	1-3 ($\times 10^{-4}$)	(41)

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PROPERTY	UNITS	CONDITIONS	VALUE	REFERENCE
Volume resistivity	ohms cm	ASTM D257	10^{16} – 10^{17}	(26, 41)
Surface tension γ	mN m^{-1}	438 K	22.5	(42)
		473 K	21.2	(43)
		495 K	20.2	(42)
Surface free energy	mJ m^{-2}	298 K (calculated from advancing contact angles)	29.0	(43)
Contact angle	degrees	H ₂ O; advancing, 298 K	116	(43)
		CH ₂ I ₂ ; advancing, 298 K	64	
Permeability coefficient	$\text{m}^3(\text{STP}) \text{ m s}^{-1} \text{ m}^{-2} \text{ Pa}^{-1}$	H ₂ O, 298 K	3.83×10^{-16}	(44)
		O ₂ , 298 K (isotropic, all pressures)	7.73×10^{-18}	(45)
		O ₂ , 298 K (12.5:1 draw ratio)	2.12×10^{-18}	(45)
		CO ₂ , 298 K (<1 atm)	2.37×10^{-17}	(46)
		CO ₂ , 298 K (50 atm)	7.50×10^{-17}	(46)
Thermal conductivity	$\text{W m}^{-1} \text{ K}^{-1}$	293 K	0.12	(47)
			0.22	
Melt flow rate	g (10 min)^{-1}	ASTM D1238, 503 K, 2.16 kg	0.2–>500	—
Speed of sound	m s^{-1}	Unoriented		(48)
		298 K	2.5×10^3	
		398 K	125×10^3	(49)
		Oriented		
		Larg. dir. 298 K	3.3×10^3	
Decomposition temperature	K	TGA in helium, Montell Profax 6501	623	(50)
Ignition temperature	K	Calculated from critical heat flux data	736	(51)
Oxygen index	%	ASTM D2863, Montell Profax 6505	17.4	(52)
Scission, G factor	—	γ irradiation		(53, 54)
		Initial	1.2	
		At doses above gel point	0.27	
Cross-linking, G factor	—	γ irradiation	0.07–0.30	(53, 54)
Producers	—	Worldwide in 1994 (see table below for examples)	~117	(55)
Capacity	ktons	Worldwide in 1994 (see table below for examples)	20,492	(55)

Some producers and capacities (from 1996)⁽⁵⁶⁾

Producer	Capacity (ktons)
Montell, Hoofddrop, The Netherlands	3,034
Targor, Mainz, Germany	1,370
Amoco, Chicago, USA	1,183
Japan Polychem, Tokyo, Japan	1,103
Fina, Brussels, Belgium	1,030

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