

Linear Alpha Olefins

Table of Contents

A Report by **NexantThinking™**

Process Evaluation/Research Planning (PERP) Program

PERP Report 2015-2 - Published October 2015

www.nexantthinking.com

Section	Page
1 Executive Summary	1
1.1 STRATEGIC AND BUSINESS OVERVIEW	1
1.2 TECHNOLOGY OVERVIEW.....	3
1.2.1 Full Range Process Technology for Linear Alpha Olefins	3
1.2.2 On-Purpose Process Technology for Linear Alpha Olefins	3
1.2.3 Upgrade of Byproduct Streams.....	4
1.3 SUMMARY OF PROCESS ECONOMICS	4
1.3.1 Cost of Producing Full Range Linear Alpha Olefins (LAOs)	4
1.3.2 Cost of Producing Butene-1	5
1.3.3 Cost of Producing Hexene-1	5
1.3.4 Cost of Producing Octene-1.....	6
1.3.5 Summary of Key Conclusions	7
1.4 COMMERCIAL MARKET OVERVIEW	8
1.4.1 Global Demand	8
1.4.2 Global Supply	12
1.4.3 Global Trade Balance.....	13
2 Introduction.....	17
2.1 HISTORICAL OVERVIEW AND INDUSTRIAL DEVELOPMENTS IN THE TECHNOLOGY	19
2.2 FULL RANGE PROCESS TECHNOLOGY FOR LINEAR ALPHA OLEFINS.....	24
2.3 ON-PURPOSE PROCESS TECHNOLOGY FOR LINEAR ALPHA OLEFINS	25
2.4 UPGRADE OF BYPRODUCT STREAMS	25
2.5 STRATEGIC AND BUSINESS CONSIDERATIONS	26
2.6 PHYSICAL AND THERMODYNAMIC PROPERTIES	29
2.7 SPECIFICATIONS	29

2.8	HEALTH AND SAFETY FACTORS	30
2.9	STORAGE AND TRANSPORTATION.....	30
3	Full-Range Technology	31
3.1	INTRODUCTION.....	31
3.1.1	Full Range Linear Alpha Olefin Chemistry	32
3.2	CHEVRON PHILLIPS.....	38
3.2.1	Process Chemistry	38
3.2.2	Process Description	39
3.2.3	Typical Product Distribution	42
3.3	INEOS	43
3.3.1	Process Chemistry	43
3.3.2	Process Description	44
3.3.3	Typical Product Distribution	46
3.4	SHELL (SHOP)	47
3.4.1	Process Chemistry	47
3.4.2	Process Description	48
3.4.3	Typical Product Distribution	54
3.5	IDEMITSU	56
3.5.1	Process Chemistry	56
3.5.2	Process Description	57
3.6	AXENS (ALPHASELECT).....	62
3.6.1	Process Chemistry	62
3.6.2	Process Description	63
3.7	SABIC/LINDE (ALPHA-SABLIN®).....	65
3.7.1	Process Chemistry	65
3.7.2	Process Description	67
3.8	UOP (LINEAR-1®)	69
3.8.1	Process Chemistry	69
3.8.2	Process Description	72
4	On-Purpose Technology	75
4.1	INTRODUCTION.....	75
4.2	ON-PURPOSE BUTENE-1 TECHNOLOGY.....	75
4.2.1	Axens (AlphaButol®), Ethylene Dimerization.....	76
4.3	ON-PROPOSE HEXENE-1 TECHNOLOGY.....	79
4.3.1	Axens (AlphaHexol™), Ethylene Trimerization	79

4.3.2	Chevron Phillips, Ethylene Trimerization	82
4.3.3	Lummus Technology (CPT), Metathesis	86
4.4	ON-PURPOSE OCTENE-1 TECHNOLOGY	90
4.4.1	Dow Chemical, Butadiene Telomerization	90
4.4.2	Sasol, Ethylene Tetramerization	95
5	Upgrade of Byproduct Streams	99
5.1	ZEON CORPORATION (GPD PROCESS), EXTRACTIVE DISTILLATION	99
5.1.1	Introduction	99
5.1.2	Process Chemistry	101
5.1.3	Process Description	101
5.2	SASOL, FISCHER-TROPSCH-DERIVED	104
5.2.1	Process Description (Hexene-1)	106
5.2.2	Process Description (Octene-1)	111
6	Process Economics	120
6.1	COSTING BASIS	120
6.1.1	Investment Basis	120
6.1.2	Pricing Basis	120
6.1.3	Cost of Production Basis	122
6.2	COST OF PRODUCING FULL RANGE LAO	123
6.3	COST OF PRODUCING BUTENE-1	130
6.4	COST OF PRODUCING HEXENE-1	133
6.5	COST OF PRODUCING OCTENE-1	138
6.6	SUMMARY OF KEY CONCLUSIONS	143
7	Commercial Applications	144
7.1	INTRODUCTION	144
7.2	POLYETHYLENE COMONOMERS	145
7.3	DETERGENT INTERMEDIATES	146
7.3.1	Detergent Range Alcohols	146
7.3.2	Linear Alkylbenzene (LAB)	147
7.3.3	Alpha Olefin Sulfonates	147
7.3.4	Alkyl Amines	147
7.4	SYNTHETIC LUBRICANTS AND OIL FIELD CHEMICALS	147
7.5	PLASTICIZERS	148
7.6	POLYBUTENE-1	148
7.7	OTHER APPLICATIONS	149

8	Regional Market Analysis	150
8.1	GLOBAL OVERVIEW	150
8.1.1	Demand	150
8.1.2	Supply	154
8.1.3	Supply/Demand Balance	155
8.2	NORTH AMERICA	159
8.2.1	Demand	159
8.2.2	Supply	164
8.2.3	Supply/Demand	164
8.3	WESTERN EUROPE	168
8.3.1	Demand	168
8.3.2	Supply	173
8.3.3	Supply/Demand Balance	173
8.4	ASIA PACIFIC	177
8.4.1	Demand	177
8.4.2	Supply	181
8.4.3	Supply/Demand Balance	183
8.4.4	Rest of World	187
8.4.5	Demand	187
8.4.6	Capacity	189
8.4.7	Supply/Demand Balance	191

Appendix		Page
A	Definitions of Capital Cost Terms Used in Process Economics	A-1
B	Definitions of Operating Cost Terms Used in Process Economics	B-1
C	PERP Program Title Index (2006 - 2015)	C-1

Figure	Page
1.1 Linear Alpha Olefins (LAOs) End-Uses.....	1
1.2 Cost of Production Summary for Full-Range Alpha Olefin Processes.....	4
1.3 Cost of Production Summary for Butene-1 Processes	5
1.4 Cost of Production Summary for Hexene-1 Processes	6
1.5 Cost of Production Summary for Octene-1 Processes	7
1.6 Global Linear Alpha Olefin Demand by Fraction.....	8
1.7 Linear Alpha Olefin Demand by End-Use	9
1.8 Global Butene-1 Demand by End-Use.....	9
1.9 Global Hexene-1 Demand by End-Use	10
1.10 Global Octene-1 Demand by End-Use.....	10
1.11 Global Decene-1 Demand by End-Use	11
1.12 Global C ₁₂ /C ₁₄ Demand by End-Use	11
1.13 Global C ₁₆ /C ₁₈ Demand by End-Use	12
1.14 Global C ₂₀ + Demand by End-Use	12
1.15 Alpha Olefin Production Capacity, Full-Range versus On-Purpose.....	13
1.16 Global Butene-1 Supply/Demand Balance.....	13
1.17 Global Hexene-1 Supply/Demand Balance.....	14
1.18 Global Octene-1 Supply/Demand Balance	14
1.19 Global Decene-1 Supply/Demand Balance.....	15
1.20 Global C ₁₂ /C ₁₄ Supply/Demand Balance	15
1.21 Global C ₁₆ /C ₁₈ Supply/Demand Balance	16
1.22 Global C ₂₀ + Supply/Demand Balance	16
2.1 Linear Alpha Olefins (LAOs) Main End-Uses.....	18
2.2 Reactions of <i>n</i> -paraffins Dehydrogenation	20
2.3 Schematic View of C ₄ Streams	21
2.4 Linear Alpha Olefins (LAOs) End-Uses.....	26
3.1 Overview of Single Stage Ethylene Oligomerization Process “Type 1”	33
3.2 Overview of Two Stage Ethylene Oligomerization Process “Type 2”	34
3.3 Theoretical Alpha Olefin Distribution by Single-Stage Ethylene Oligomerization	35
3.4 Theoretical Alpha Olefin Distribution by Two-Stage Ethylene Oligomerization	36
3.5 Comparative Theoretical Alpha Olefin Carbon Distributions.....	37
3.6 Chevron Phillips Full-Range LAO Process	40
3.7 Chevron Phillips Full-Range LAO Process, Reaction Section	41
3.8 Chevron Phillips Full-Range LAO Distributions.....	42

3.9	INEOS Full-Range LAO Process	45
3.10	INEOS Full-Range LAO Distributions	46
3.11	Overview of Shell's Higher Olefins Process	47
3.12	Shell Higher Olefins Process (SHOP), Oligomerization Section	49
3.13	Shell Higher Olefins Process (SHOP), Alpha Olefin Separation Section	51
3.14	Shell Higher Olefins Process (SHOP), Isomerization, and Disproportionation (I/D) Section	53
3.15	Speculative SHOP Mass Balance	55
3.16	SHOP LAO/LIO Distribution	55
3.17	Overview of Idemitsu Alpha Olefin Process – Linealene	56
3.18	Idemitsu Process Schematic View	58
3.19	Idemitsu Process Separation Train Type I	59
3.20	Idemitsu Process Split Separation Train Option	60
3.21	AlphaSelect™ Carbon Number Distribution	62
3.22	Axens AlphaSelect Selective Ethylene Oligomerization Process for LAOs	64
3.23	alpha-SABLIN® Catalytic Cycle	66
3.24	alpha-SABLIN® Carbon Number Distribution	66
3.25	SABIC/Linde Alpha-SABLIN® Full-Range LAO Process	68
3.26	UOP LINEAR-1 Full-Range LAO Distribution	71
3.27	UOP LINEAR-1 Full-Range LAO Process	73
4.1	Mechanism for Selective Ethylene Dimerization	76
4.2	Axens AlphaButol® Ethylene Dimerization Process for Butene-1	78
4.3	Mechanism for Selective Ethylene Trimerization	79
4.4	Axens AlphaHexol™ Ethylene Trimerization Process for Hexene-1	81
4.5	Chevron Phillips Trimerization Catalysis	83
4.6	Chevron Phillips Hexene-1 Process, Trimerization, and Separation Sections	85
4.7	Hexene Isomers Thermodynamic Equilibrium	87
4.8	Simplified Block Flow Diagram of Lummus CPT Process for Hexene-1 Production	88
4.9	Dow Butadiene Telomerization Process for Octene-1	94
4.10	Sasol's Proposed Mechanisms for Ethylene Tetramerization	96
4.11	Sasol Ethylene Tetramerization Process for Octene-1	97
5.1	Illustrative Integrated C ₄ Complex	99
5.2	Zeon Extractive Distillation Process for Butene-1	102
5.3	Schematic of Sasol's Secunda Complex	104
5.4	Sasol Fischer-Tropsch-Derived Alpha Olefin Distribution	105
5.5	Block Flow Diagram for Sasol Hexene-1 Process from Synthol	106

5.6	Sasol Hexene-1 Recovery from Fischer-Tropsch Liquids Process, Pre-Treatment, and Etherification.....	108
5.7	Sasol Hexene-1 Recovery from Fischer-Tropsch Liquids Process, Super-Fractionation, and Extractive Distillation	110
5.8	Block Flow Diagram Schematic of Octene Train I.....	111
5.9	Block Flow Diagram Schematic of Octene Train II.....	112
5.10	Sasol/Linde Azeotropic Distillation Process	114
5.11	Sasol Octene-1 Process from Mixed C ₇ Stream	116
6.1	Cost of Production Summary for Full-Range Alpha Olefin Processes.....	124
6.2	Cost of Production Summary for Butene-1 Processes	130
6.3	Cost of Production Summary for Hexene-1 Processes	133
6.4	Cost of Production Summary for Octene-1 Processes	138
7.1	Alpha Olefin Market Segments.....	144
7.2	Global LAOs Demand by End-Use, 2014	145
8.1	Global Linear Alpha Olefin Demand by Fraction.....	150
8.2	Linear Alpha Olefin Demand by End-Use	151
8.3	Global Butene-1 Demand by End-Use.....	151
8.4	Global Hexene-1 Demand by End-Use.....	152
8.5	Global Octene-1 Demand by End-Use.....	152
8.6	Global Decene-1 Demand by End-Use.....	153
8.7	Global C ₁₂ /C ₁₄ Demand by End-Use	153
8.8	Global C ₁₆ /C ₁₈ Demand by End-Use	154
8.9	Global C ₂₀ + Demand by End-Use	154
8.10	Alpha Olefin Production Capacity, Full-Range versus On-Purpose.....	155
8.11	Global Butene-1 Supply/Demand Balance.....	155
8.12	Global Hexene-1 Supply/Demand Balance.....	156
8.13	Global Octene-1 Supply/Demand Balance	156
8.14	Global Decene-1 Supply/Demand Balance.....	157
8.15	Global C ₁₂ /C ₁₄ Supply/Demand Balance	157
8.16	Global C ₁₆ /C ₁₈ Supply/Demand Balance	158
8.17	Global C ₂₀ + Supply/Demand Balance	158
8.18	North America Alpha Olefin Demand by Fraction and End-Use	159
8.19	North America Alpha Olefin Demand by End-Use	160
8.20	North America Butene-1 Demand by End-Use	160
8.21	North America Hexene-1 Demand by End-Use	161
8.22	North America Octene-1 Demand by End-Use	161

8.23	North America Decene-1 Demand by End-Use	162
8.24	North America C ₁₂ /C ₁₄ Demand by End-Use	162
8.25	North America C ₁₆ /C ₁₈ Demand by End-Use	163
8.26	North America C ₂₀ + Demand by End-Use	163
8.27	North America Butene-1 Supply/Demand Balance	165
8.28	North America Hexene-1 Supply/Demand Balance	165
8.29	North America Octene-1 Supply/Demand Balance	166
8.30	North America Decene-1 Supply/Demand Balance	166
8.31	North America C ₁₂ /C ₁₄ Supply/Demand Balance	167
8.32	North America C ₁₆ /C ₁₈ Supply/Demand Balance	167
8.33	North America C ₂₀ + Supply/Demand Balance	168
8.34	Western Europe Alpha Olefin Demand by Fraction	168
8.35	Western Europe Alpha Olefin Demand by End-Use	169
8.36	Western Europe Butene-1 Demand by End-Use	169
8.37	Western Europe Hexene-1 Demand by End-Use	170
8.38	Western Europe Octene-1 Demand by End-Use	170
8.39	Western Europe Decene-1 Demand by End-Use	171
8.40	Western Europe C ₁₂ /C ₁₄ Demand by End-Use	171
8.41	Western Europe C ₁₆ /C ₁₈ Demand by End-Use	172
8.42	Western Europe C ₂₀ + Demand by End-Use	172
8.43	Western Europe Butene-1 Supply/Demand Balance	173
8.44	Western Europe Hexene-1 Supply/Demand Balance	174
8.45	Western Europe Octene-1 Supply/Demand Balance	174
8.46	Western Europe Decene-1 Supply/Demand Balance	175
8.47	Western Europe C ₁₂ /C ₁₄ Supply/Demand Balance	175
8.48	Western Europe C ₁₆ /C ₁₈ Supply/Demand Balance	176
8.49	Western Europe C ₂₀ + Supply/Demand Balance	176
8.50	Asia Pacific Alpha Olefin Demand by Fraction and End-Use	177
8.51	Asia Pacific Alpha Olefin Demand by End-Use	177
8.52	Asia Pacific Butene-1 Demand by End-Use	178
8.53	Asia Pacific Hexene-1 Demand by End-Use	178
8.54	Asia Pacific Octene-1 Demand by End-Use	179
8.55	Asia Pacific Decene-1 Demand by End-Use	179
8.56	Asia Pacific C ₁₂ /C ₁₄ Demand by End-Use	180
8.57	Asia Pacific C ₁₆ /C ₁₈ Demand by End-Use	180

8.58 Asia Pacific C ₂₀ + Demand by End-Use	181
8.59 Asia Pacific Butene-1 Supply/Demand Balance	183
8.60 Asia Pacific Hexene-1 Supply/Demand Balance	183
8.61 Asia Pacific Octene-1 Supply/Demand Balance	184
8.62 Asia Pacific Decene-1 Supply/Demand Balance	184
8.63 Asia Pacific C ₁₂ /C ₁₄ Supply/Demand Balance.....	185
8.64 Asia Pacific C ₁₆ /C ₁₈ Supply/Demand Balance.....	185
8.65 Asia Pacific C ₂₀ + Supply/Demand Balance	186
8.66 Rest of World Butene-1 Demand by End-Use	187
8.67 Rest of World Hexene-1 Demand by End-Use	187
8.68 Rest of World Octene-1 Demand by End-Use	188
8.69 Rest of World C ₁₂ /C ₁₄ Demand by End-Use.....	188
8.70 Rest of World Butene-1 Supply/Demand Balance	191
8.71 Rest of World Hexene-1 Supply/Demand Balance	191
8.72 Rest of World Octene-1 Supply/Demand Balance	192
8.73 Rest of World Decene-1 Supply/Demand Balance	192
8.74 Rest of World C ₁₂ /C ₁₄ Supply/Demand Balance	193
8.75 Rest of World C ₁₆ /C ₁₈ Supply/Demand Balance	193
8.76 Rest of World C ₂₀ + Supply/Demand Balance	194

Table	Page
1.1 Strategic/Business Considerations	2
1.2 Cost of Production Summary for Hexene-1 Processes	6
2.1 List of Linear Alpha Olefins	17
2.2 C ₄ Stream Compositions	22
2.3 Alpha Olefin Composition per Feedstock.....	23
2.4 Industrial Full-Range Alpha Olefin Ethylene Oligomerization Processes	24
2.5 Strategic/Business Considerations	27
2.6 Properties of C ₄ to C ₂₀ Linear 1-Olefins	29
2.7 Commercial 1-Butene Specifications	29
2.8 Commercial 1-Hexene Specifications	30
3.1 Theoretical Alpha Olefin Distribution by Single-Stage Ethylene Oligomerization	35
3.2 Theoretical Alpha Olefin Distribution by Two-Stage Ethylene Oligomerization	36
3.3 Indicative Alpha Olefin Composition	57
3.4 C ₄ to C ₁₀ Product Distribution with AlphaSelect™	62
3.5 Typical Product Characteristics from ALPHASELECT	63
4.1 Typical Specifications of Butene-1 from AlphaButol	76
4.2 Typical Specifications of Hexene-1 from AlphaHexol™.....	80
4.3 Typical Analysis of a Crude C ₄ Stream from a Naphtha Cracker	90
4.4 Product Distribution for Dow's Octene-1 Process	92
4.5 Results from Sasol's Ethylene Tetramerization Patent	95
5.1 C ₄ Stream Compositions	100
5.2 C ₄ Component Properties in DMF (boiling point of 153 °C at 1 bar).....	101
5.3 Relative Volatilities in Various Polar Solvents.....	103
5.4 Sasol Fischer-Tropsch-Derived Mixed Hexene/Hexane Stream Composition	106
5.5 Assumed Sasol Mixed C ₇ Feedstock Composition	117
5.6 Boiling Points of Various Octanol Isomers	118
5.7 Boiling Points of Components in Dehydration Reactor Effluent.....	119
6.1 Prices of Raw Materials, Utilities, and Labor.....	121
6.2 Cost of Production Summary for Full-Range Alpha Olefin Processes.....	123
6.3 Cost of Production Estimate for Full-Range Alpha Olefins Process: Chevron Phillips, Ethylene Oligomerization, USGC.....	125
6.4 Cost of Production Estimate for Full-Range Alpha Olefins Process: INEOS, Ethylene Oligomerization, USGC.....	126
6.5 Cost of Production Estimate for Full-Range Alpha Olefins Process: Shell (SHOP), Ethylene Oligomerization, USGC	127

6.6	Cost of Production Estimate for Full-Range Alpha Olefins Process: SABIC/Linde (Alpha SABLIN), Ethylene Oligomerization, USGC	128
6.7	Cost of Production Estimate for Full-Range Alpha Olefins Process: Axens (AlphaSelect), Ethylene Oligomerization, USGC	129
6.8	Cost of Production Summary for Butene-1 Processes	130
6.9	Cost of Production Estimate for Butene-1 Process: Axens (AlphaButol®), Ethylene Dimerization, USGC	131
6.10	Cost of Production Estimate for Butene-1 Process: Zeon, Extractive Distillation, USGC	132
6.11	Cost of Production Summary for Hexene-1 Processes	133
6.12	Cost of Production Estimate for Hexene-1 Process: Chevron Phillips, Ethylene Trimerization, USGC	134
6.13	Cost of Production Estimate for Hexene-1 Process: Axens (AlphaHexol™), Ethylene Trimerization, USGC	135
6.14	Cost of Production Estimate for Hexene-1 Process: Lummus (CPT), Metathesis, USGC	136
6.15	Cost of Production Estimate for Hexene-1 Process: Sasol, Extraction from Synfuels, South Africa	137
6.16	Cost of Production Summary for Octene-1 Processes	138
6.17	Cost of Production Estimate for Octene-1 Process: Dow Butadiene Telomerization, USGC	139
6.18	Cost of Production Estimate for Octene-1 Process, Sasol, Ethylene Tetramerization, USGC	140
6.19	Cost of Production Estimate for Octene-1 Process: Sasol, Extraction from Synfuels, South Africa	141
6.20	Cost of Production Estimate for Octene-1 Process: Sasol, C ₇ s Extraction from Synfuels via Octanol, South Africa	142
8.1	North America Alpha Olefin Capacity, 2014.....	164
8.2	Western Europe Alpha Olefin Capacity, 2014.....	173
8.3	Asia Pacific Alpha Olefin Capacity, 2014	182
8.4	Rest of World Alpha Olefin Capacity, 2014	190

Nexant Thinking™

Process Evaluation/Research Planning



The NexantThinking™ Process Evaluation/Research Planning (PERP) program is recognized globally as the industry standard source for information relevant to the chemical process and refining industries. PERP reports are available as a subscription program or on a single report basis.

Contact Details:

New York: Marcos Nogueira Cesar, Vice President, Global Products, E&CA: Nexant Thinking™
Phone: + 1-914-609-0324, e-mail: mcesar@nexant.com

New York: Heidi Junker Coleman, Global Programs Support Manager
Phone: + 1-914-609-0381, e-mail: hcoleman@nexant.com

Nexant, Inc. (www.nexant.com) is a leading management consultancy to the global energy, chemical, and related industries. For over 38 years, Nexant has helped clients increase business value through assistance in all aspects of business strategy, including business intelligence, project feasibility and implementation, operational improvement, portfolio planning, and growth through M&A activities. Nexant has its main offices in San Francisco (California), White Plains (New York), and London (UK), and satellite offices worldwide.

Copyright © by Nexant Inc. 2015. All Rights Reserved.