Future Trends in Polyolefin Materials

Kenneth B. Sinclair

STA*Research, 14006 23rd Place SE, Snohomish, WA 98290, USA

SUMMARY**:** Over the past decade, the depth and breadth of catalyst technologies for addition polymerization have expanded tremendously, both for Ziegler-Natta catalysts as well as for single-site catalysts. It seems that every day someone adds a new element to this understanding, opening up new or improved ways to make specific polymers with targeted characteristics and performance.

Combinatorial techniques are accelerating this process of discovery even further, perhaps by one order of magnitude. Synergistic interactions between catalyst technologies and production process technologies are resulting in step-change increases in manufacturing efficiency and in product range capabilities. The net result is that the industry and its scientists seem to have perfected the process of creating ***potential*** value at a tremendous rate.

The critical challenge now facing the industry is how to realize this potential value: how to connect the technology to the market. In this, speed is of the essence. Until the connection is made, the commercial value of the technology is nothing more than intangible "potential." Meanwhile, the patents are aging and competitors lurk around the corner to steal the potential before the developer has the chance to reap his just rewards. Fortunately, technology-leading companies are developing new efficient and fast business processes to speed products to market, and the full value of new technologies is being realized.

Fifteen families of SSC-based polymers have been developed over the past decade; 12 of these are already commercial, and 3 are approaching commercialization. Of these fifteen, 11 are totally new to the industry, and 4 are new versions of established families (HDPE, LLDPE,PP, EPDM). The industry required 25 years to commercialize the first 4 families, and an additional 20 to fully develop markets for them. How will it deal with the introduction of three times as many new families in one third of the time, while concurrently developing the new SSC-based versions of traditional polymers? How soon will the *potential* created by technological innovation be translated into tangible value? Some projections are given.

Introduction

Projections of future trends in any industry must start with the definition of the current status of the industry as the base point for the projections. We can then speculate about the future based on events in the recent past and on the characteristics of the industry as revealed by its history.

In the polyolefin materials industry, the recent past has been perhaps the most exciting

 CCC 1022-1360/00/$ 17.50+.50/0

period in the industry's history, with dramatic developments in all branches of industry technology: catalysts, polymerization processes, products, applications, and in business procedures and research techniques. These events will have equally dramatic consequences for the industry as they play out through the next few decades. In this paper, we first discuss these recent developments in the context of the longer term history of the industry. This leads to a definition of where we are in the polyolefin materials industry, and where we seem to be going through the next decade.

How new technologies are commercialized: The lessons of history

If we look back at the long term history of the polymers industry over the past century, we can see that technology development has been cyclical. There have been three cycles of revolutionary developments followed by longer periods of evolutionary developments, and we are now early in the fourth cycle (Figure 1).

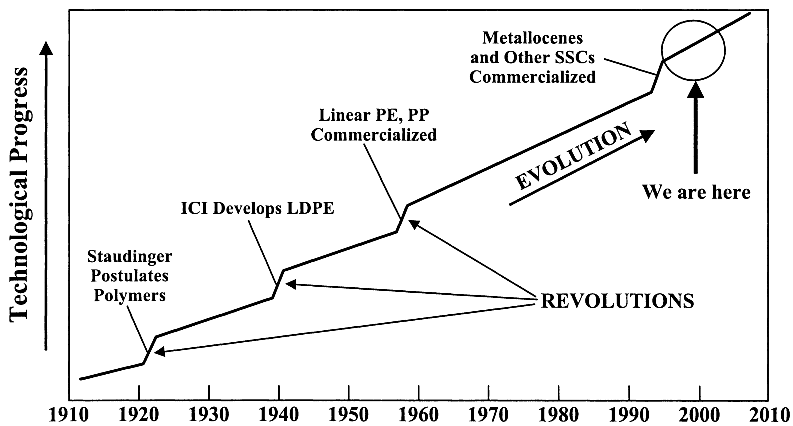

Fig. 1: Technology revolution/evolution cycles in the polymer industry.

The first revolution in the 1920s was founded in the fundamental understanding of the nature of polymers. The second in the early 1940s involved the development of commercially viable technologies to make low density polyethylene (LDPE) by a high pressure free radical polymerization. This was the genesis of polyolefins as we know them today, an industry that currently produces about 80 million ton/year of plastic materials. The third revolution in the 1950s was based on the discoveries of insertion polymerization catalysts by Ziegler, Natta and others. This was the genesis of polypropylene (PP), high density polyethylene (HDPE) and linear low density polyethylene (LLDPE). The fourth revolution that is now flowing into the market is based on metallocene and other single-site catalyst (SSC) technologies.

A more detailed illustration[1] of the cyclical nature of polymer technology development has been given by Dr. Joseph Miller, then chief technology officer and senior vice president for Research & Technology at E. I. Du Pont de Nemours & Company. As he described it, the history of technology development within the DuPont company shows four cycles between 1927 and 1996, with each cycle beginning with a discovery phase followed by a consolidation phase (Figure 2).

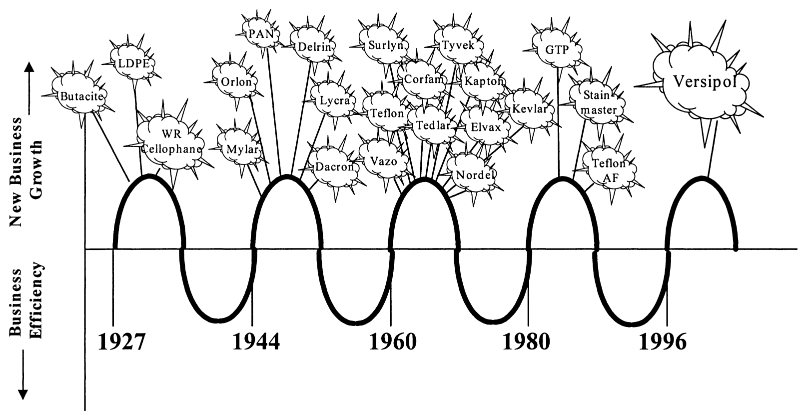

Fig. 2: The 15 – 20 year discovery research/consolidation cycles at DuPont.

In the „discovery research" phase of the cycle, the focus of the company is on developing new technologies that will create opportunities for new business growth. It is a highly innovative period in which basic science is translated into *potential* wealth. In the consolidation phase this potential wealth is captured and retained, primarily through new market creation. The focus of the company switches from scientific innovation to market innovation and increased business efficiency. As this phase plays out, the company begins to look for new avenues for business growth, and a new cycle begins.

Dr. Miller has also described another phenomenon that is perhaps a root cause of the cyclicality in technology: bursts of innovation seem to occur when streams of knowledge meet. For example, in the 1960s and 1970s, the streams of knowledge in biology and in computer science came together in a burst of innovation that we now call biotechnology. One spin-off of this confluence was the development of molecular modeling software (for example, that developed by Biosym) used initially in understanding and designing drugs. In the 1970s and early 1980s, this biotechnology stream came together with polymeric materials science to give computer-based polymer simulation and quantitative structure/property prediction programs for polymers. The confluence of computer science and plastics processing technology (not shown in the Figure) occurred at about the same time, resulting in sophisticated mold and part design that boosted use of all plastics across a broad range of industries, and particularly that of PP.

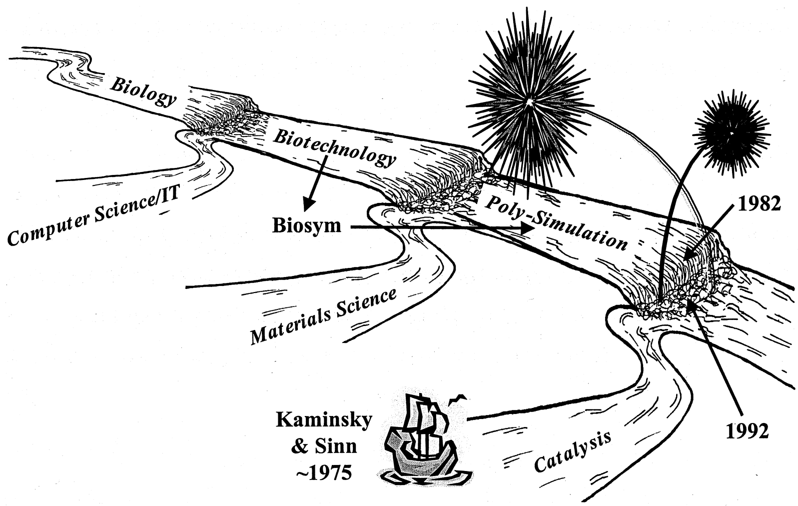

Fig. 3: The confluence of streams of knowledge gives rise to bursts of innovation.

Finally, in the 1980s the knowledge of polymer simulation and molecular modeling met the stream of advanced catalysis embodied in metallocenes and other SSCs to give the burst of innovation that we have seen over the past 10-15 years. The result has been a veritable explosion of new polymer families that were previously unknown or too difficult to make to be commercially feasible products. The rate of innovation is truly revolutionary in nature, as illustrated in Table 1. In the 55 years since the first commercial production of a polyolefin (LDPE) in the mid-1940s, the industry developed and commercialized four polyolefin product families. In the 10 years since 1990, the industry has introduced a further eleven polyolefin families, ten of which are viable only because of advanced single-site catalysis. (PCHE is made by hydrogenation of polystyrene rather than directly by advanced polymerization catalysis).

Table 1. The current technology revolution has resulted in an unprecedented rate of new product introduction: 11 new polymer families in 10 years compared to the historical 4 families in 55 years.

HDPE	55 YEARS	Traditional Families
(L)LDPE		
PP		
EPDM		
Plastomers (Exact™, Affinity™, Luflexen™)	10 YEARS	New SSC-Based Families
Ethylene/norbornene elastomers (EPO™)		
Ethylene/octene elastomers (Engage™)		
Ethylene/styrene interpolymers (Index™)		
Elastomeric/soft PP homopolymers (EHPP, FPO)		
Liquid polyolefins (Trilene™, Paramins™, Versipol™?)		
Ethylene/CO copols. (polyketones Carilon™, Ketonex™)		
Poly(substituted)norbornene (Avatrel™, Appear™, Duvcor™)		
Ethylene/cyclic olefin copolymers (Topas™, Apel™)		
Syndiotactic polystyrene (Questra™, Xarec™)		
Polycyclohexylethylene (PCHE, “Peachy”)		

As further illustration of the extent of this revolution, the industry has introduced more than 33 new product lines in 10 years, 21 of which are SSC-based variations of the 11 new generic families, and 12 are derivatives of the 4 traditional polyolefin families. A sampling of the non-traditional products is given in Table 2. Most of these are fully commercial products but a few are not yet at that stage. For example, the Versipol liquid polyolefins are not yet commercial, although some other novel Versipol polymers may be. Also, the status of the ethylene/carbon monoxide copolymers is uncertain at this time. Carilon was a fully commercial product launched by Shell in 1995 that found numerous applications, notably in automotive fuel systems. Shell built two commercial production plants, and had developed a low-cost gas phase process that it expected to use in a new 150,000 ton/year unit. However, in late 1998 Shell decided to divest a range of polymer businesses, including the Carilon business, and these were sold in 1999/2000. A buyer for Carilon could not be found and Shell closed its plants and withdrew its products from the market in February 2000. Similarly, the Ketonex products and technology were put up for sale as the result of BP‘s strategic decision to sell its engineering plastics businesses. Commercialization of Ketonex is less advanced than Carilon, and a buyer has not yet been found.

Table 2. A partial list of SSC-based polyolefin product lines introduced over the past 10 years that are members of new, non-traditional product families.

Product Lines Based on New Polyolefin Families		
New Generic Family	**Trade Name**	**Producer**
Plastomers	Exact	ExxonMobil
	Affinity	Dow
	Evolue-P	Evolue Japan#
	Luflexen	Basell
	Kernel	Japan Polychem
Ethylene/norbornene elastomers	EPO	Idemitsu
Ethylene/octene elastomers	Engage	DuPont Dow
Ethylene/styrene interpolymers	Index	Dow
Soft/elastomeric PP homopolymers	FPO	Idemitsu
Ethylene/cyclic olefin copolymers	Topas	Ticona
	Apel	Mitsui
Ethylene/carbon monoxide copolymers	Carilon	Shell
	Ketonex	BP
Poly(substituted)norbornenes	Avatrel	BF Goodrich
	Appear	BF Goodrich
	Duvcor	BF Goodrich
Liquid polyolefins	Trilene	Uniroyal
	Versipol	DuPont
Syndiotactic polystyrene	Questra	Dow
	Xarec	Idemitsu
Polycyclohexylethylene	PCHE or „Peachy“	Dow

Evolue Japan is a joint venture of Mitsui Chemicals and Sumitomo Chemical

A sampling of SSC-based product lines that are extensions of traditional product families is given in Table 3. This list is not complete in that there are several companies in the early stages of SSC-based product commercialization that have not yet coined a new trade name. Some SSC-based product lines are being introduced under existing brand names. For example, Asahi, ExxonMobil and LG Chemical all have metallocene-based HDPE product lines that are commercial. Several other companies are developing SSC-based traditional products such as BP, Chisso, Equistar, Mitsui and Solvay, and these are expected to be commercialized within a year or two.

Table 3. A partial list of SSC-based polyolefin product lines introduced over the past 10 years – Additions within traditional product families.

Product Lines Based on New Polyolefin Families		
Traditional Generic Family	**Trade Name**	**Producer**
Linear polyethylenes	Boracene MD/LLDPE	Borealis
	Exceed LLDPE	ExxonMobil
	Elite LLDPE	Dow
	Evolue LLDPE	Evolue Japan[#]
	Finacene HDPE	ATOFINA
	Harmorex LL	Japan Polyolefins
	mPact LLDPE	Chevron Phillips
Polypropylene	Achieve mPP	ExxonMobil
	Finacene miPP	ATOFINA
	Finaplas msPP	ATOFINA
	Metocene mPP	Basell
EP(D)M elastomers	Nordel IP mEPDM	DuPont Dow

Evolue Japan is a joint venture of Mitsui Chemicals and Sumitomo Chemical

It is clear from these tables that major changes are taking place in polyolefins technology and products that are redefining industry boundaries. These revolutionary changes are being driven by SSC technologies. At the same time, evolution of traditional Ziegler-Natta catalysis is continually expanding the market reach of traditional polyolefins, stimulating demand growth. It is perhaps more exciting and rewarding to be involved in the industry at this time than at any time in the past 40-50 years.

The commercial benefits of single-site catalysts for polyolefins

The high level of activity in commercialization of SSC technologies indicates that industry leaders believe that there will be commercial benefits that flow from them. These benefits on the polymer production side will be technical, but leading ultimately to more effective utilization of capital. Benefits downstream of the polymer production plants will be in the form of greater market utility and greater market value.

One example of the technical benefits in the polymer production plant is the expansion of the product range accessible to each & every major process technology. This is illustrated in Figure 4 which compares the product ranges of PE production technologies with and without the use of SSC technologies.

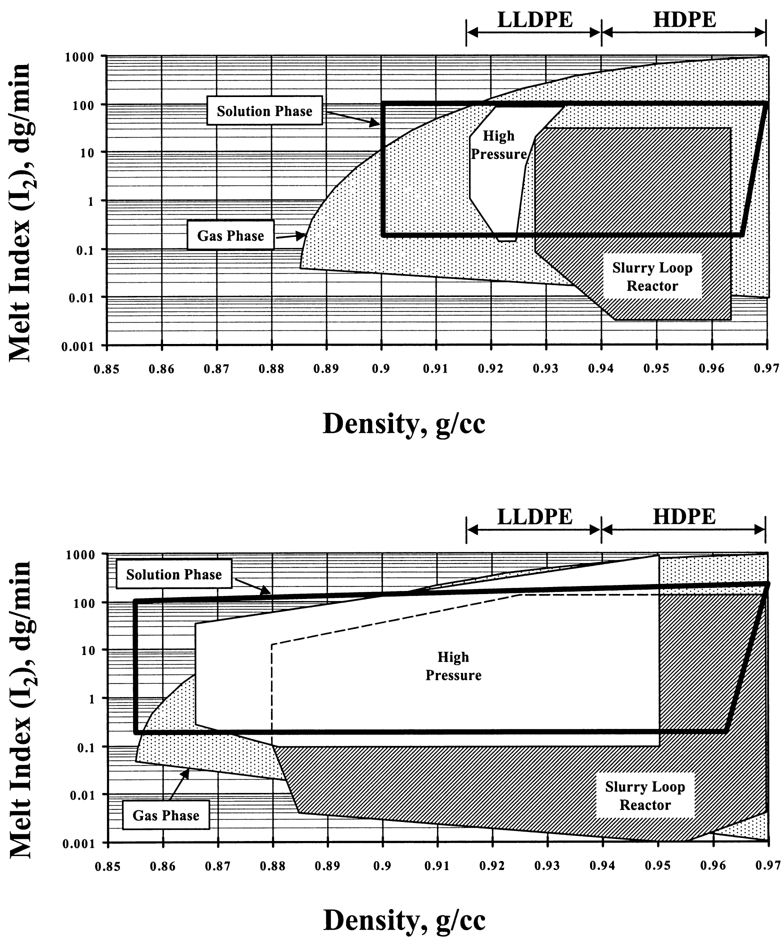

Fig. 4: Product ranges of leading PE processes in terms of melt index (Condition E) and product density; upper figure – before the introduction of SSC technologies; lower figure – with SSC technologies. Source: STA*Research estimates.

Further benefits for polyolefin production can be seen in the extension of maximum reactor productivity beyond the limits achievable with Ziegler-Natta technologies. For example, in gas phase PE processes, SSCs are highly active and very responsive in copolymerization, allowing the producer to change the composition of the reactor gas to increase productivity. When this is combined with the latest improvements in heat removal from gas phase reactors, the result can be a doubling of reactor space-time yield, with obvious implications for plant investment cost. To illustrate this, Figure 5 shows the trend in reactor residence time (inverse of reactor productivity) for typical gas phase processes from their commercial introduction in the late 1960s to 2000 and beyond. Between 1960 and 1995, reactor residence times decreased by a factor of 5 due to improvements in catalysis as well as reaction engineering, but reductions seemed to be approaching a limit of about 2 hours residence time. With the introduction of SSCs, this limit could be removed to increase reactor output by another 100% by halving the required residence time. Thus, a reactor sized in 1968 to make about 40,000 tons/year PE could now theoretically make over 450,000 tons/year, and ultimately it could reach about 600,000 tons/year. The limitation is no longer in polymerization efficiency but in down-stream polymer handling machinery.

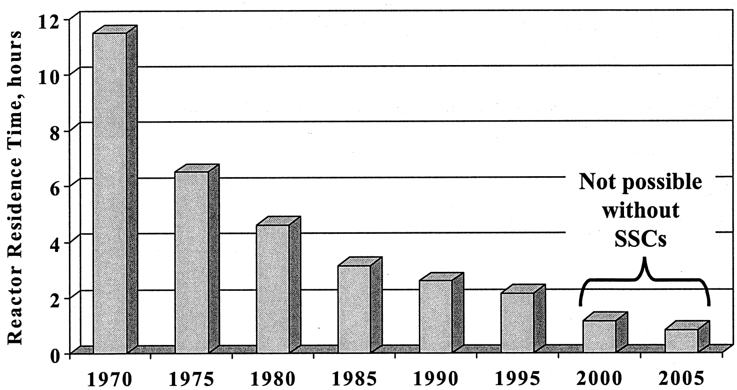

Fig. 5: Progressive improvement in required reactor residence time for gas phase PE processes from 1968 to 2005; SSC technologies are key in facilitating increases of more than 100% in reactor output by halving required residence time. Source: STA*Research interpretation of the Unipol™ process licensed by Univation Technologies.

The downstream benefits of SSC technologies derive from the greater market utility of SSC-based polymer products. Greater market utility is ultimately translated into increased revenues for the polymer producer, and the increased revenues justify continuing investment in research and in production facilities. The benefits can therefore be quantified in terms of incremental revenues: the difference between (expected) revenues with full implementation of SSC technologies, and the revenues that (would have) result solely from continued exploitation of traditional technologies. There are three categories of incremental revenues flowing from SSCs:

- Increased polymer sales due to new market creation, and expansions of existing markets, e.g.:
  - – New polymers such as plastomers and olefinic elastomers like ESI
  - – New applications such as bags for extended shelf life fresh salads
  - – Metallocene iPP for better fibers & nonwovens
  - – Soft metallocene iPP for elastic fibers & to replace fPVC
- Higher price premiums on higher performance products for new as well as established markets.
- Small but welcome price premiums on direct "cannibals" of current products.

The first category is the most important but it is often overlooked because of the difficulty of projecting new markets for new products, neither of which exist at the time of projection. Some reasonable estimates can be made, however, on the basis of theoretical technology capabilities and perceived ultimate market needs. The logical basis is that new technologies are the drivers of new market creation, and therefore of demand growth, a fact proven by past history of polyolefin market development. For example, the history of PP consumption in North America from 1960 to the late 1990s shows very clearly the effects of new technologies on PP demand growth. Figure 6 shows PP consumption per capita growing from zero in 1960 toward an ultimate 2020 potential that in the early 1980s was expected to be about 9 kg/capita. New catalyst, process and processing technologies introduced in the early 1980s boosted this ultimate 2020 expectation by a factor of 3 to about 27 kg/capita, and demand growth continues to follow this boosted trendline. The impact of the new technologies is measured by the large increment in consumption between the 9 kg/capita trendline and the new 27 kg/capita trendline.

Of course, the early 1980 technologies were not the final answer, and new more advanced technologies continued to be introduced. The latest surge is based on SSC technologies as well as advanced Ziegler-Natta technologies, and we will see the benefits of these in accelerated demand growth in the years to come.

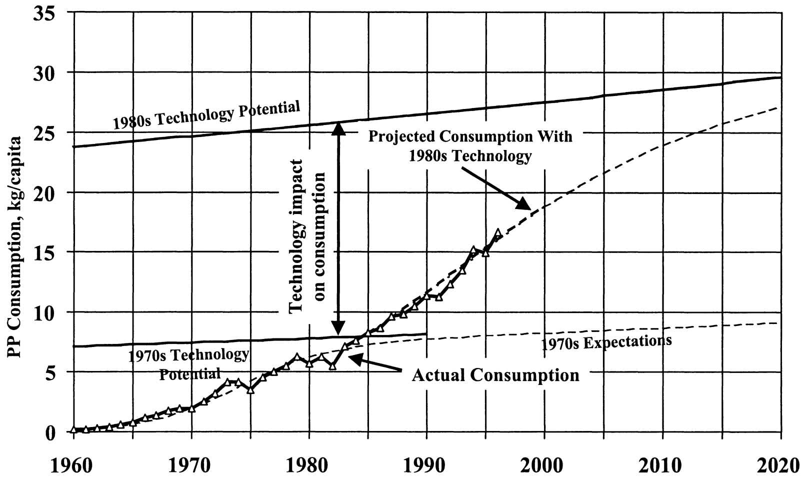

Fig. 6: The historical development of PP demand growth in North America; new technologies introduced in the early 1980s boosted ultimate potential consumption per capita by a factor of three. Source: STA*Research estimates.

In summary, the downstream benefits of SSC technologies can be assessed on the following basis:

- New market creation will flow from SSC technology, and the new value added for the polyolefin producer will be the spread between monomer and generic polymer prices on this additional demand.
- These new SSC products will, by definition, satisfy previously unmet market needs, and they will command a price premium compared to existing products in the same generic family. This will give an additional revenue increment for this new polymer demand.
- SSC-based "cannibal" products – upgraded direct replacements of existing products - will gain either a small price premium and/or a production cost advantage, as well as a competitive advantage (higher market share).

Further discussion on these value assessments is given below.

Challenges & solutions in SSC technology commercialization

In the early-1980s Shell estimated that it could cost about **$1 billion** to take a totally new polymer from discovery through to full commercial production (presumably a production scale of about 25,000 to 50,000 tons/year or higher). The history of SSC commercialization over the past 15 years seems to support such high cost estimates: the leaders in commercialization of SSC-based PE may each have spent a cumulative $400 to $600 million on technology and market development before seeing their first positive cash flow. Based on the number of patents applied for and issued in the field of SSCs, the global industry may have spent a cumulative $5 billion on these technologies by about 2000, as illustrated in Figure 7. And yet research continues at an unrelenting pace.

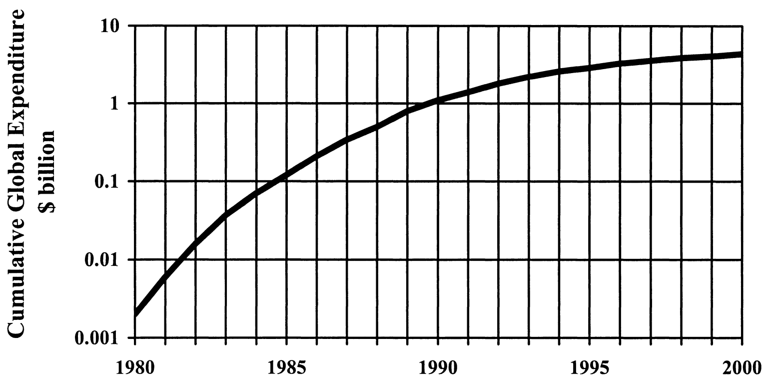

Fig. 7: Estimated global cumulative investment in research and development in SSC-based technologies & products. Source: STA*Research estimates.

Concerns have been expressed that the industry will never be able to recover this investment. These high costs of new product commercialization have also led to some recent casualties, including, perhaps, Shell's own Carilon polyketones and the elastomeric PP homopolymers being developed by BP/Amoco/Stanford/BBA.

There are a number of factors that indicate, however, that such high development costs will not be an insurmountable barrier to commercialization of SSC-based products and technologies. The first of these comes from a study at the New York University School of Business[2] that assessed the historical return on R & D expenditures in the chemical industry. The preliminary results published in September 2000 indicated that those companies that spend the most on R & D also receive the greatest return on each dollar spent, while those investing the least received the lowest return on each of the few dollars that they did spend. The study ranked companies by the intensity of their R & D expenditures, and assessed their returns as follows:

Company Classification	Operating Profits on R & D Investment
Intense spenders	\$3.10/\$ invested
Large companies	\$2.86/\$ invested
Average size companies	\$2.60/\$ invested
Small companies	\$1.79/\$ invested
Low spenders	\$1.39/\$ invested

Following this argument, the companies investing the most in SSC technology development should reap the greatest returns on their R & D expenditures. However, research and innovation will, by definition, create only *potential* wealth. This potential wealth can be accessed by commercialization of products based on the new technologies. In other words, there are good reasons for cycles of discovery research to be followed by periods of commercialization and consolidation as described above for the case of DuPont (Figure 2).

Studies have been carried out to investigate whether the potential wealth flowing from SSC technologies can be realized through new market creation, and whether the magnitude of this wealth exceeds the approximately \$5 billion cumulative expenditure on technology development. The methodology used followed the logic of value creation described above. The results for ethylene-based SSC products alone are summarized in Table 4.

Table 4. Estimated net present values (NPVs) of incremental revenue streams derived from SSC-based ethylene polymers; global basis; expressed in 1998 US\$ based on 20-year cash flow streams from 1998 to 2017; 12% discount rate[3].

Estimated NPV of incremental revenues derived from SSC-based PE	
LLDPE + Plastomers	\$13-\$24 billion
HDPE	\$4 - \$15 billion
Total PE	\$17- \$39 billion

Source: STA*Research estimates

These numbers represent the total value of the technologies to the global PE production industry, and the technology developers and polymer producers will take only their just shares of this value. In many cases, the technology developers will also be polymer producers, so these companies will reap the full benefits. For the rest, producers will license technologies from developers, pay a license fee or royalty, and keep the residual for themselves. Either way, it is clear that the wealth likely to be generated by commercialization of SSC-based PEs will more than cover the total \$5 billion cumulative costs of SSC technology development for all polymers. The companies that are quickest to commercialize SSCs will reap the greatest benefits.

Even when companies are reassured that heavy R & D expenditures can be recovered by future exploitation, the funding of new product development efforts poses a significant challenge: companies might need to find $400-$1 billion to cover cumulative costs for commercialization of *each* new SSC-based product. If we take Dow as an example, Tables 2 &3 indicate that it is commercializing seven families of SSC-based products, and at least an additional two are under development. In normal circumstances, this would imply that Dow needs to find about $2 to $7 billion to fund the commercialization of its SSC technologies, technologies that could ultimately return an incremental $10 to $40 billion or more to the company.

Fortunately, Dow seems to have developed systems to overcome this enormous funding requirement. The solution seems to be rooted in information technology and in a concept initially espoused by Himont in the early 1980s. This concept (as interpreted by STA*Research in its application to PP) holds that, if a company has thorough knowledge of what properties can be achieved through variations in structure and composition of PP, and if it has catalyst and process technologies that can make almost any practical structure and composition, then it can effectively make polymers for almost any application, from engineering polymers to elastomers, with essentially the same assets. Dow seems to have adapted this concept to its SSC technologies and solution process, applying sophisticated and linked models to speed the transformation of a perceived market need to a finished, and optimally tailored, polymer product. The result is what could be called a “six-day machine” for new product development, as shown in Figure 8.

In concept, the precision and versatility of Dow’s SSC systems allows it to make exactly the (co)polymer it wants and, by use of its sophisticated polymer modeling software, it can design this polymer to have properties that closely match market needs. It can then program its solution-phase commercial production plant to make precisely the product the market wants at the first pass, without the need for semicommercial production trials and extended product development runs.

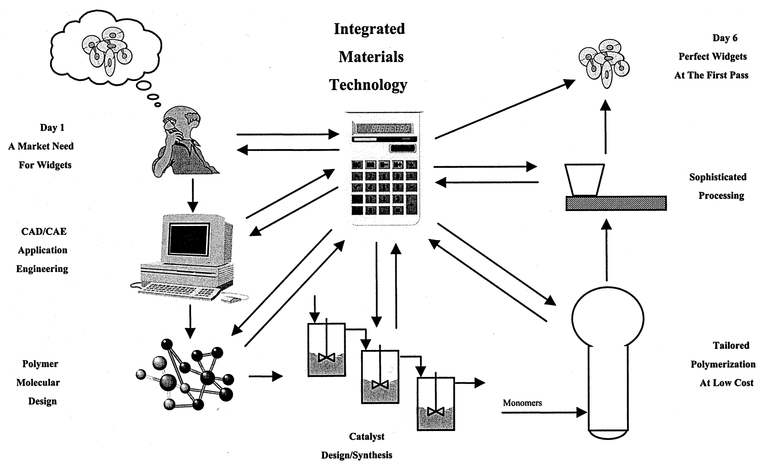

Fig. 8: Dow's „Six-Day Machine" concept – as interpreted by STA*Research.

Dow has trademarked this system as SixDays™ and has reported examples of its application in which a market request for a completely new grade (of an established product line) has been fulfilled through delivery of the first commercial batch of a perfectly matched product within six days of receipt of the original market request. This is a tremendous acceleration of the new product development process that would normally require months of technical design and perhaps two or three full-scale production trials. Obviously, a company cannot spend much money in the six day elapsed time, so development costs are also dramatically reduced.

Sophisticated as Dow's system is, it is not yet perfect, and new product design for new applications (outside the traditional application domain) still takes some time, but much less than before. It has reported the reduction in typical new product development cycle time from 56 months to 7 months, from start of product design to customer qualification. Concurrently, its success rate has increased from 30% to 89%. Overall, these tools and techniques may have reduced Dow's cumulative new product funding requirements by one order of magnitude, from $2 - $7 billion to $200 - $800 million for its current seven SSC-based families.

This example of Dow is typical of a broad industry trend that will have a major impact on the outlook for polyolefins generally: the rate of technology innovation is accelerating across the industry and through much of the value chain. This is illustrated in Figure 9. Combinatorial techniques are accelerating the discovery of new catalysts and new polymers, and reducing R & D costs, perhaps by one order of magnitude. For example, Symyx, a Californian company specializing in the application of combinatorial techniques to catalysis, performed 250,000 experiments in 1999 alone, with only a handful of employees. At the polymerization stage, the productivities of polymerization reactors has been boosted tremendously by such technologies as super-condensed mode (SCM™) technology developed by ExxonMobil, as discussed above. The application of SSCs in traditional polyolefin production processes is expanding their product range capabilities into new and interesting areas. However, so far, there have been far fewer developments to accelerate the translation of new technologies through processing to the market place. In other words, the industry is accelerating its creation of *potential* wealth, but still faces the traditionally slow stages of final market development. This is perhaps the greatest challenge facing the industry and particularly those developing novel SSC-based products.

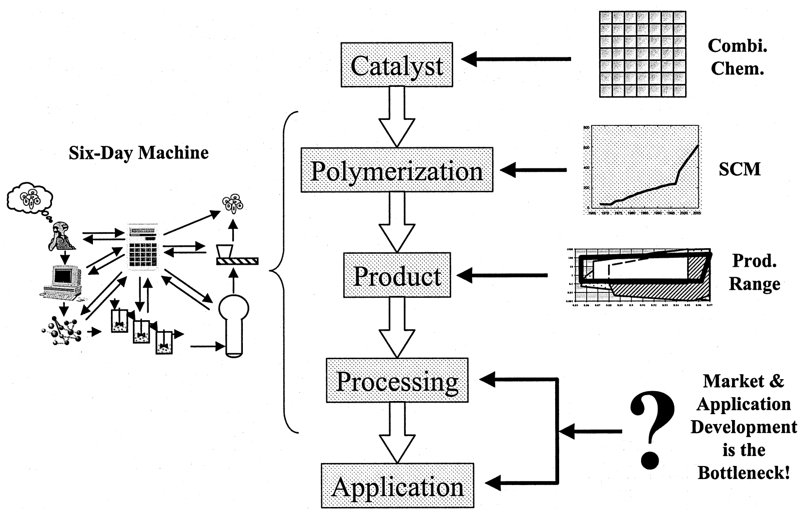

Fig. 9: Technology accelerators in the polyolefin value chain are creating bottlenecks in the final product commercialization stage.

Once more, Dow is addressing this problem (as probably are other industry leaders) by modeling applications such as the energy absorption profile of impact protection structures for automobiles, and even complete pedestrian kinematics to be able to design cars that offer increased pedestrian safety. However, the sheer diversity of plastics applications means that a tremendous effort is still required from the industry before the speed of applications development catches up with the speed of polymer technology development.

A progress report on SSC commercialization

So far, we have described the history of how new technologies are commercialized in the polyolefins industry, as well as the dramatic developments of the last decade, derived principally from SSC technologies. We can now move on to defining where the industry stands with respect to SSC commercialization, and then project how these technologies may roll out in the future.

Based on expectations in the early- to mid-1990s, metallocene-polyolefin market development is (in the opinion of STA*Research) about two years behind schedule. Prime reasons for this are:

- **Patent disputes** delayed exploitation through lack of freedom to operate: Exxon vs. Dow, Phillips, Fina; Dow vs. DSM, Exxon; Exxon vs. Mobil, UCC; etc.
- **Industry consolidations** caused temporary suspensions or delays in SSC commercialization during the merging process: BASF + Hoechst >> Targor, Elenac + Montell >> Basell; Exxon + Mobil; BP + Amoco + Arco + Solvay; Chevron + Phillips; Dow + UCC; Total + Fina + Elf; DSM + Huels; Borealis + PCD; JPO, Japan Polychem, Mitsui + Mitsui Toatsu + Sumitomo; etc.
- **Corporate "re-engineering"** has broken the flow of technology commercialization: technology thrusts have been diluted or diverted; induced "corporate amnesia" in some cases
- The severe, decade-long **recession** in Japan plus the 1997/98 Asian financial crisis put many programs on hold.
- **Technical difficulties**: adaptation of SSCs to gas phase PE processes; commercialization of 2nd generation mPP

In spite of all these obstacles, the commercialization of SSC-based ethylene polymers is proceeding generally according to expectations, and is now entering a phase of global market acceleration. In the case of SSC-based propylene polymers, however, progress seems to be well behind schedule, and it is useful to examine why this may have occurred.

When Hoechst announced[4] the development of their high performance stereoselective zirconocene catalyst systems in 1992, the initial promise of metallocene PP seemed to be very good:

- Very broad MW range
- Very narrow MWD
- Both syndiotactic and isotactic PP
- Broad comonomer capabilities
- Extremely high activity
- By implication:
  - High stiffness & strength in homopolymers
  - Super-impact copolymers

Eight years later, the progress in mPP commercialization is disappointing:

- Only 20-30 grades available world-wide
- Syndiotactic PP seems to be "small"
  - Perhaps 100 kt by 2005 world-wide
- Some commercial success in fibers
  - Spunbond & melt blown non-wovens
  - Filtration media
- Some commercial success in molding
  - Homopolymers for thinwall injection molding
- As yet unfulfilled promise elsewhere
  - Homopolymers for fine denier fibers & BOPP
  - Random & impact copolymers for film & molding

Why the slow progress? It seems that mPP has no technical "killer flaws" that would preclude it from practical market application, but it is a more complex technology than at first it appeared and it has some technical hurdles still to overcome. These include in particular catalyst supporting technologies that retain the stereoselectivity and activity characteristics of homogeneous systems. It is also true that the initial expectations of the *rate* of mPP market growth were too high: there are limitations in manufacturing, both technical and logistic. Also, 1st generation mPP products were inadequate in some respects (e.g. bonding, processability) and this led to slow market acceptance.

All these inadequacies and technical problems can be solved, and solutions have already been described for most of them. The potential for mPP to create new frontiers in PP properties & applications is therefore definitely there, and this potential will eventually be exploited. When it is, it should add ~0.5%-2% to annual growth in PP consumption through 2020.

Thus, the prospects for mPP commercialization are looking up, and there are positive developments in the industry that should accelerate the process:

- Merging of BASF and Shell PE/PP interests:
  - BASF + Hoechst PP + Shell PE + ROW + Hoechst PE + Montell PE Europe + Himont [Montedison + Hercules] + Spherilene >>Basell, a powerful new force in the industry and a strong proponent of SSC technologies.
- Basell "will license its metallocene patent rights to all interested third parties," thereby spreading the load of commercialization.
- Japan Polychem & ATOFINA separately completed their 1st commercial production runs of mPP random copolymers (125°C m.p.) in 2000.
- Idemitsu commercialized FPO mPP homopolymers in 2000.

Projections of the impact of SSCs on future markets for polyolefins

With the foregoing discussion as a backdrop, we have prepared projections of global demand growth for PP and PE that include the impact of the introduction of SSC technologies, generally following the logic already described. We identified and quantified the potential for new products in new and existing applications, and then modeled the growth of consumption from zero at the time of introduction, moving toward full potential in the future.

The results[5] for PP are shown in Figure 10 for the 15-year period from 1995 (the first year of introduction on a commercial scale) to 2010. It is our expectation that 2000 will prove to be the "take-off" year for mPP demand growth. We conclude that the introduction of 1st and 2nd generation mPP products will add about 5.5 million tons to global PP demand by 2010, boosting global annual average growth rate by a little over 1% per year for the next decade. In addition, these mPP products will displace about 6.5 million tons of Ziegler-Natta PP – the cannibal products. Thus, total demand for mPP products in 2010 will be about 12 million tons, equivalent to about 20% of the total

global consumption. Penetration rates in some regions will be significantly higher than this.

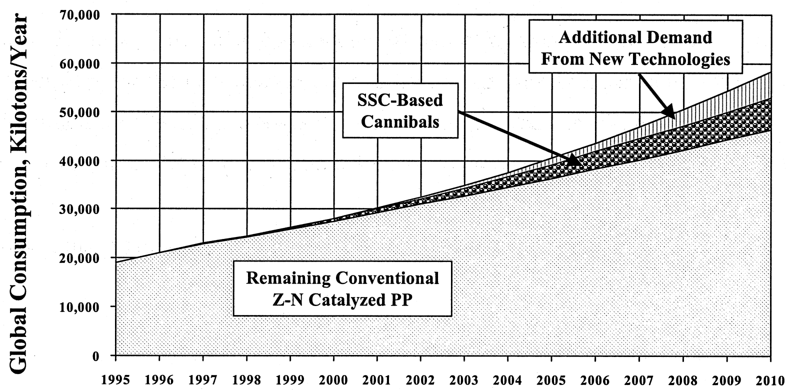

Fig. 10: Global PP demand projection showing the effects of new technologies.

The projected outlook[3] for high pressure LDPE and LLDPE is shown in Figure 11, and for HDPE in Figure 12. Global demand for high-pressure LDPE will peak in about 2

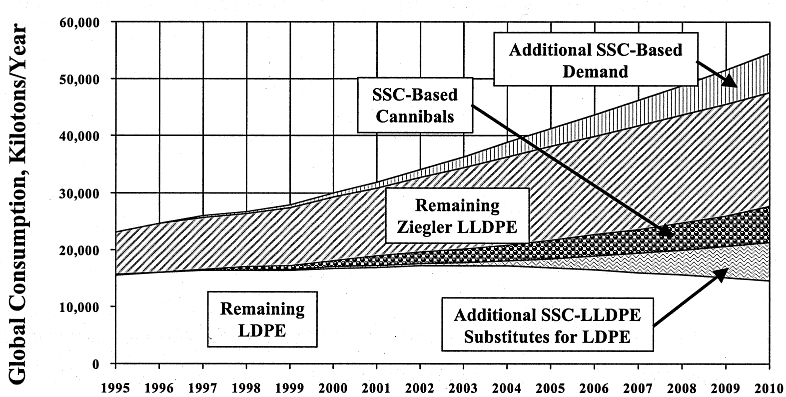

Fig. 11: Global low density PE demand projection showing expected penetration by SSC-based products.

years and will contract by about 2 million tons/yr (to ~14.5 million tons) by 2010. LDPE demand in Asia & other developing regions will continue to grow for several years, requiring ~8-10 new world-scale high-pressure units, each with a capacity of 200,000 to 300,000 tons per year in one line. Old and small LDPE lines (< 50 kt/yr) will face terminal competition from these very large new lines, and many are likely to close or be replaced during the next decade.

SSC-based linear PEs, HDPE, LLDPE and plastomers, will expand total global PE markets by about 6% in 2005 and 15% in 2010 (including demand for plastomers) [3]. SSC-based low-density resins will account for about 19% of total LDPE+LLDPE demand in 2005, and about 37% in 2010 (including plastomers). SSC-based HDPE resins will account for 5% of global HDPE in 2005 and about 20% in 2010. These latter markets will be comparatively slow to develop, with the period between 2010 and 2015 seeing the greatest rate of penetration by the new products.

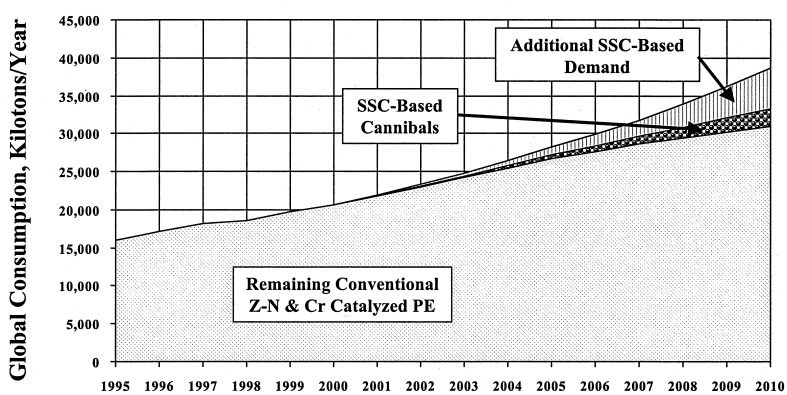

Fig. 12: Global high density PE demand projection showing the effects of the introduction of SSC-based products.

Overall, markets for SSC-based PEs are growing at over 45% per year (on a base of 1-$2x10^6$ tons) and significant impact on most regional markets for PE commodity & specialty grades will be seen within 1-2 years. Total SSC-capable capacity for commodity & specialty polyolefins (PE, PP, plastomers, EPDM, specialties) now exceeds 3 million tons/year, and is growing rapidly. Global demand for linear ethylene-based resins made with SSCs is expected to reach about 28 million tons in 2010, including LLDPE, HDPE and plastomers, so that total demand for SSC-based PE and PP will reach about 40 million tons in 2010, a very large quantity indeed. Demand for SSC-based specialties such as EPDM and the eleven new families described earlier will be in addition to this, adding perhaps about 800,000 to 1 million tons/year to this total.

The next "Big Thing" in polyolefin markets

The polyolefins industry continues to generate tremendous volumes of technical papers and patents concerned with SSC technologies and their products. This is what can be expected in a true industry revolution. The pace will likely continue through the next 5-10 years before slowing to a "maintenance" level.

It is now time to look for the next "big thing" in polyolefin technology, the breakthrough in technology that will initiate the next revolution, for there will surely be one.

A review of the most recent literature reveals that **polymer nanocomposites** could be the kernel of that next revolution. Nanocomposites typically comprise nano-sized clay platelets individually dispersed in a polymer matrix. These very small particles give a tremendous boost to polymer physical properties at levels of incorporation of only a few percent. Although this field has been researched for more than a decade, and some products have been available for about that length of time, the technology seemed to have some intractable obstacles that hindered commercialization. Recent developments have changed this situation, and the current status of the technology is as follows:

- The key technology breakthrough was made only in 1998.
- Much of the experimental work with natural clays done before 1998 is invalid, and so are previous conceptions of technology potential.
- Clay impurities added with the platelets destroyed impact strength & elongation, impaired barrier properties, and contributed to haze & lower clarity, cumulatively "killer" flaws of the technology. Once identified, this problem is being quickly overcome.

The question now is, what will nanocomposites contribute to polyolefins? Based on a detailed review of the patent and technical literature, as well as an independent analysis of the entire value chain, we have concluded that the following enhancements are now achievable in polyolefins:

- Dramatically improved stiffness & HDT with negligible loss of impact strength (if any).
- Highly filled performance at low density and without affecting aesthetic properties such as clarity and gloss.
- High gas barrier properties at low clay loadings.
- Significant contributions to flame retardance.

- Simple and low cost exfoliation technologies are available.

The effect of nanocomposites on plastics markets can be assessed in a similar way to that described above for SSC technologies: first assess the value creation *potential* of nanocomposites, then model the realization of this potential over time. Such a study has recently been completed[6], with the following broad conclusions:

- Nanocomposite technology can be applied to **any** polymer to improve physical properties.
- Polymers likely to benefit the most from nanocomposite technologies are nylons, polycarbonates, PET, PE & PP.
- PP will gain more than any other polymer in terms of market growth & differential value.
- Large-scale applications are on the brink of commercialization.
- Market penetration will be rapid compared to the rate of penetration of SSC technologies. Nanocomposite technologies can be applied and developed by hundreds of compounders and plastics conversion companies compared to a handful of companies developing SSCs.
- Demand for PP nanocomposites alone will be measured in millions of tons per year by 2010.

As an illustration[7], Figure 13 summarizes the value *potential* of new technologies developed or being developed for PP in the period from about 1993 to about 2006. These applications are the result of the commercialization of three classes of technology: advanced Ziegler-Natta catalysts, stereoselective SSCs, and nanocomposites. It indicates that Ziegler-Natta technologies still have a lot of value potential, some of which is already in the early phases of realization, and others are still to come. There are numerous potential applications for SSC-based PP, most of that are not yet visible in the marketplace. Nanocomposite value potential is all in the future, and many of the applications have high potential value. Some are very large. It is going to be an interesting and stimulating decade for the polyolefins industry.

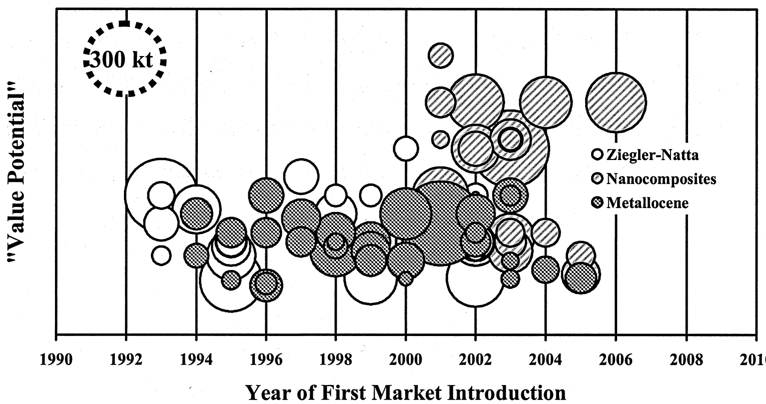

Fig. 13: Market value potential for PP created through new technologies.

Conclusion

So where are we in the polyolefins technology cycle?

- There has been a veritable explosion in new product introductions with outstanding, even unique, properties (excluding nanocomposites).
- Almost 20 new families of polymers based on advanced Ziegler-Natta catalysts and SSCs have been introduced in the past 10 years.
- At least 40 new product ranges have been introduced, 33 of which are based on the use of SSCs; more are in the pipeline.
- 11 entirely new families of SSC-based polymers have reached (semi)commercial status, excluding parallel developments.
- We are at the cusp of exponential growth in a new wave of technology-driven innovation: in products, processes, and catalysts.
- Prospects for renewed growth & profitability are the best they have been in decades.

A statement that provides one of the best capsules of the outlook for SSC technologies, and therefore for the polyolefins industry, was given by Ed Gambrell, now Dow's Business Group President for Market Facing Business Units, as follows:
"SSC technology will have a greater financial impact on the polymer industry than any technology change in history."

1. Joseph A. Miller, „Discovery Research Re-Emerges in DuPont," Research & Technology Management, January-February 1997.
2. Initial results from a study commissioned by the Council for Chemical Research (CCR), as reported in C & EN, 78, 38, 15-16, September 2000.
3. „The Financial Impact of Metallocenes on the Global Polyethylene Industry," STA*Research, Snohomish, Washington, November 1998.
[4] Dr. W. Spaleck presentation at the PP'92 conference, Zürich, Switzerland, October 1992, Maack Business Services.
Spaleck, W. et al. (**1992**), „High Molecular Weight Polypropylene Through Specifically Designed Zirconocene Catalysts," Angew. Chem. Int. Ed. Engl. 31,10,1347-50
Spaleck, W. et al. (**1993**), „New Isotactic Polypropylenes by Metallocene Catalysts," MetCon'93 conference, Houston, Texas (May 26-28), 1993, Catalyst Consultants Inc.
[5] „Ultimate Polypropylene Market Potential," Bins & Associates, Sheboygan, Wisconsin, August 1999, and STA*Research estimates.
[6] „Nanocomposite Market Opportunities," Bins & Associates, Sheboygan, Wisconsin, December 2000.
[7] Estimates by Bins & Associates and STA*Research.