RETEC

POLYOLEFINS V

CONFERENCE ON POLYOLEFINS

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GRADE CHANGE FLEXIBILITY - DEFINED, DETERMINED, COMPARED

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GRADE CHANGE FLEXIBILITY — DEFINED, DETERMINED, COMPARED Kenneth B. Sinclair

Introduction

All polyethylene and polypropylene processes are required to produce a number of different product grades in the same plant. Each grade is produced in sequence in production runs which may vary in length from less than a day to a number of weeks. When the production sequence for all grades in the plant's slate has been completed, the production cycle begins again.

Grade changes and scheduling the production of various product grades are probably the sources of more headaches for production managers than any other aspect of their responsibilities (slide 1). By definition, each grade change requires that the plant's steady-state operating conditions be disturbed. The unsteady conditions during the change dramatically increase the risk of unforeseen difficulties that could lead to plant shutdown. Slurry and gas phase polyethylene processes are particularly at risk because they operate close to the melting point of the polymer. Peak temperatures occurring during grade transition can exceed the melting point of the polymer and lead to solidification of the reactor contents, resulting in prolonged plant shutdown to allow for reactor cleanup.

The scheduling of the production of each grade is ultimately the responsibility of the product manager who must reconcile conflicting objectives of his sales, production, and accounting staffs. The sales staff would prefer an almost unlimited range of grades be available to increase market accessibility and the likelihood of making a sale. In addition, the sales staff would like to have orders for any grade filled instantly, irrespective of the size of an order and its time frame. However, the production staff cannot fill an order for any specific grade on demand because the grades must be made in a predetermined sequence, moving from one grade to the next. Doing so minimizes the differences in product properties and plant operating conditions between the starting and target grades of each grade change. The "cushion" between the opposing demands of sales and production departments is the product inventory, which the accounting and management staff view as a wasteful drain on the company's resources and profits.

Management techniques to minimize the cost of inventories for specific types of sales and demand fluctuations are well understood and widely used in industry. Management understands the other half of the problem — production scheduling — much less well because timing depends not only on the time response characteristics of the production plant, but also on the chemistry of the products and of the polymerization reaction. Managers are aware, however, that the penalties of grade changes are a significant cost element in overall plant economics and one that can be prohibitive if a plant is operated with an inappropriate product slate.

Matching a product slate with individual processes and production lines has thus become an increasingly important aspect of competitive positioning. Evaluating and managing this aspect is difficult. The disparity between the chemistry and mechan-

ics of production processes is wide, and grade change flexibility cannot be readily expressed in terms of familiar engineering or accounting units.

This paper defines process grade change flexibility and describes a methodology for comparing the flexibilities of various processes on a uniform basis. The method can be used to translate flexibility directly into bottom-line cost penalties for any product slate from any process.

Definition

Grade changes in any polymerization plant are complex and test the operators' capabilities to the limits (slide 2). During the transition, many plant operating variables are changing simultaneously. Some variables (e.g., reactor temperature, pressure, and catalyst inventory) are the prime determinants of reaction rate, whereas other variables determine product properties and the overall plant energy and material balance. All these variables are interdependent, as well as being independently variable. At any point in a transition, one or more of these variables will be the critical determinant of the highest speed at which a change can take place and still maintain safe plant operating conditions. To give some idea of how critical these variables can be, in response to only minor changes in reactor conditions a high-pressure LDPE reactor can go from stable operation to explosive decomposition in a matter of seconds, (slide 3). Thankfully, this particular excursion is only a computer simulation.

Three basic aspects of grade changes determine cost penalties for overall plant economics (slide 4): The first aspect for many grade changes is maintaining safe operating conditions. To do so the reaction rate or plant production rate must be slowed before the change is initiated. Slide 3 gave a good illustration of the main reason for this reduction in plant output. Lower output during the transition translates to a loss of production when averaged over a year's operation, or a reduction in the effective plant capacity.

The second aspect affecting cost is the production of off-specification product from the reactor during the grade transition. The quality of this product will be intermediate between that of the starting grade and that of the target grade; it may thus have to be sold at a discount as "widespec" product.

The third aspect relates to the amount of product that must be held in inventory to ensure that sufficient supplies of any one grade are available for sale while the reactor is producing other grades in the product slate. These inventories must be financed by working capital, and the interest on that capital amounts to a cost penalty for plant economics.

Estimating the lost production time and widespec product elements of a specific grade change is illustrated in **slide 5** which tracks polymerization rate during the change from production of grade G1 to grade G2. In this example, the polymerization rate must be slowed to 88% of nameplate capacity at the beginning of the change to maintain safe reactor conditions. The polymerization is held at the reduced rate while the reactor conditions change towards those required for the tar-

get grade. At point C the polymerization rate begins to be gradually increased within the plant safety limitations, finally reaching steady state conditions for the target grade at point E. In the time between leaving the specification limits for the starting product (point A) until the specification limits for the target grade (point D) are attained, widespec product for this grade change is produced. The lost production time can be estimated as the difference between what the reactor could have produced during the grade changeover and the actual production during that change.

A typical polyolefin plant may have a production cycle containing five reactor grades, with each grade being made in proportion to the total demand. The plant produces each grade in turn for a number of hours proportionally to the demand pattern. The sequence in which the product grades are made is selected to minimize the differences in quality among grades. For example, if grade G1 is HDPE, if grade G5 is LLDPE, and if grades G2, G3, and G4 are intermediate density polyethylenes, a change from production of G1 to G5 cannot be made without going through the densities of the intermediate products (slide 6). The production sequence would then be dictated by order of decreasing density between grades G1 and G5, and by order of increasing density between G5 and G1. This aspect of preset production sequence distinguishes polyolefin technologies from most other multiproduct process systems, and it is a characteristic that significantly complicates production scheduling.

The inventories of each product grade (slide 7) that must be held to avoid "stockout" penalties depends on the position of each grade in the production cycle and on sales patterns. Some grades are produced only once per cycle and, assuming a steady sales rate, the inventory of these grades will vary regularly between a maximum and minimum (upper figure). Other grades are made twice in each production cycle in different amounts, and inventories for these may vary in a bimodal cycle (lower figure). The minimum inventory of each grade that must be held will be determined by order frequency and the average size of individual orders. An excess inventory will also be required because each reactor grade is usually sold in a number of additive variants: Inventories of each variant must be kept. Thus, the total inventory will consist of the minimum amount required to even out the production and ordering cycles, plus an excess amount held for additive variants and for the prevention of stockout penalties.

The minimum inventory amount required to even out the cyclic nature of production and demand obviously depends on the length of the production cycle. Operation with a long production cycle of several weeks requires higher minimum inventories than does a short production cycle of a few days. In other words, the cost of carrying inventory varies inversely with the length of the production cycle and therefore with the number of grade changes made in a year. If the cost penalties of widespec and lost time are plotted together with the cost of carrying inventories (slide 8), a minimum total cost represents the optimum balance between the length of the production cycle and the cost of carrying inventories. This minimum occurs when the cost of carrying inventories is equal to the cost of grade changes. The

grade change flexibility of the process can be defined in terms of this minimum cost.

Determination

To determine grade change penalties for a specific plant and product slate they must be measured or calculated. To calculate the penalties, it is first necessary to determine the reaction conditions for the starting grade and the target grade, and then to construct a mathematical model of the reaction kinetics, as well as of the other variables affecting the speed of grade change (e.g., thermal inertia of the system, mass inertia of the reactor contents, process back–mixing effects). Building such a model requires a detailed knowledge of polymer, process, and plant characteristics. However, the model is a prerequisite to analysis of grade changes because each change is a unique event differing from all other changes in the production cycle. Without a model, it is impossible to predict which plant variable (see slide 2) will control the speed of each change and the amount of lost time and widespec product involved.

Once a mathematical model of the polymerization system has been constructed, it can be used to simulate each grade change in the production cycle, giving quantitative estimates of widespec product and lost time for each change and for the whole cycle. Associated cost penalties can then be derived as shown in slide 9. The cost penalty of grade changes is defined here as variable "A" and is the sum of the widespec amount multiplied by the price discount, plus the lost time amount multiplied by the contribution to revenues that the lost production could have made. This cost penalty per cycle is independent of the length of the production cycle. Similarly, the cost of carrying inventory can be defined as variable "B" which is derived by multiplying the total amount of inventory by its unit value and the interest rate on working capital. The inventory cost penalty varies with the length of the production cycle and also with the number of reactor product grades.

Analyzing grade change flexibility is simplified by defining two ratings: a difficulty rating and a penalty rating. The difficulty rating is the average cost of lost time and widespec per change in the production cycle, and is given by "A," divided by the number of changes in the cycle. A high difficulty rating implies that, on average, the quality difference between starting and target grades for each change is large; thus widespec and lost time amounts are large. A low difficulty rating implies that the qualities of the starting and target grades are quite similar, and little or no widespec and lost time are involved.

The penalty rating is a square root function because it is related to the minimum point of the total cost parabola shown in the previous slide. The rating can be used for directly deriving the average cost per reactor grade of widespec, lost time, and inventory cost penalties. These two ratings can be calculated for any product slate from any plant by estimating widespec and lost time amounts for one production cycle. The ratings represent the optimum tradeoff between inventory and cycle length, and they therefore determine the number of production cycles per year, as well as the total amount of inventory that must be carried.

To illustrate this procedure, **slide 10** shows our estimates of a typical optimum mode of operation for a fluidized bed gas phase linear polyethylene plant. The product slate is a relatively easy one from the point of view of grade changes, having just three reactor grades that differ only in melt indices. The difficulty rating for this slate (for a specific industry cost base) is 12, which has units of cost per grade change. As shown, the optimum mode of operation for this slate would be 22 production cycles per year, indicating a cycle length of a little more than 2 weeks and a grade change every 3 or 4 days. Total product inventory would be equivalent to about 2.6 weeks of production. The amount of widespec product would be 2.6%. In this particular case, most of this widespec product could probably be backblended in small amounts with the prime product, but the degree to which this would be possible would depend on product specification limits and the length of the production time between grade changes. However, assuming that all the widespec product slate translates to about \$6 per tonne, or 0.27¢ per pound.

A difficult product slate from the same plant is shown in slide 11. This slate has 6 reactor product grades of similar melt index, but with densities varying between 0.920 gm/cc up to 0.958 gm/cc. The difficulty rating of this slate is 48, 4 times that of the "easy" product slate. With such a high difficulty rating, the frequency of grade changes must be reduced by operating with a much longer production cycle of 6 weeks, and with a grade change occurring approximately once every 10 days. Product inventories are much higher — exceeding 2 months — and the widespec product amounts to 10% of total production. Average total penalties for this slate amount to about \$22 per tonne or 1¢ per pound, which is a significant cost indeed. In fact, grade change penalties for this slate would be the largest single production cost element under the producer's control (slide 12). It is about 5 times the cost of monomer inefficiencies in a typical process, and it is significantly higher than the total cost of utilities to make the polyethylene, such as cooling water, steam, and electricity. Such a high cost would not normally be tolerated, and thus this product slate is not appropriate for the process in this specific industry cost environment. However, it does illustrate the importance of grade change penalties and their effect on overall production economics. We have found that grade change penalties for appropriate product slates from all polyolefin processes (and particularly from polypropylene processes) are always significant, and in many cases they are large enough to change the ranking of processes in terms of overall costs.

It is at this point that most producers and technology licensors throw their hands in the air and proclaim that their technology has no widespec production and never loses a minute of operating time in the year. In any case, what is the point of calculating grade change penalties for product slates that are not commercially feasible? These calculations provide very useful information. We calculated grade change penalties for eight product slates from this process; each slate is different with respect to the number of grades and the specific grades included. We found that a plot of difficulty rating against penalty rating for all eight slates could be well correlated by a single straight line (slide 13). These slates included polyethylene

grades covering the full range of product available in the marketplace from HDPE homopolymers to LLDPE copolymers of densities below 0.920 gm/cc and with melt indices ranging from a high-load melt index of 4 dg/min to a conventional melt index of more than 100 dg/min. We can think of no valid reason why any product slate that could be devised for this process should not also fall close to that straight line plot. We conclude that the slope of that difficulty/penalty plot and its position in the difficulty/penalty continuum are fundamental characteristics of this reaction system. These characteristics define its grade change flexibility.

To prove this point, we determined grade change characteristics for a whole range of polyethylene and polypropylene processes (slide 14), and here I mean "Determined" with a capital "D." We built mathematical models of 24 distinct polymerization systems for polyethylene and polypropylene, and developed product recipes for about 320 product grades. These grades were then mixed together to form 90 product slates, for each of which we determined grade change characteristics and difficulty and penalty ratings. These 90 product slates involved nearly 800 individual grade changes, practically all of which were unique and required individual simulation. We found that every process we examined exhibited grade change characteristics that could be quite well correlated on a straight line plot of difficulty rating versus penalty rating. The slope and the position of the line were different for each process, reflecting their unique grade change characteristics.

Comparison

Having determined the difficulty/penalty characteristics of each process, we then looked at how grade change penalties could be meaningfully compared for processes with fundamentally different reaction systems. Such comparisons are made difficult by the almost infinite variability in actual production schemes (slide 15). It is highly probable that no two polyolefin plants around the world make the same product slate. The molecular structure and properties of polymers made by various processes also differ. In addition, the grade change techniques used in each process will be different and will also vary with the composition of the product slate. Reactor residence times vary by a factor of about 450:1, but the estimated range of grade change penalties is much narrower. The situation is further complicated by claims that grade change penalties can be minimized or even eliminated.

The penalty minimization aspect provides a clue to a method that can be used to compare fundamentally dissimilar processes. It is best described by analogy with the wheel. A difficult product slate, such as that described earlier, can be likened to a square wheel: The large changes in product quality result in a rough ride for the plant. To ease the ride grade change difficulty can be reduced in several ways (slide 16):

- Fewer reactor product grades will reduce grade changes in each cycle.
- The product slate for each production line can be arranged so that the difference in quality between grades from each line is small, even to the point of having overlapping specification limits.

- Widespec product made during a grade changeover can be segregated and then backblended into the prime product at a level of perhaps 5% or 10%, thereby eliminating the widespec discount penalty.
- The polymer inventory in the reactor can be reduced before grade change is initiated by, for example, doubling the rate of takeoff for a short time before the change is initiated. The amount of widespec is thereby reduced because intermediate product is mixed with a smaller amount of product already in the reactor.
- · Sophisticated computer models and control systems can be used to optimize grade transitions to a degree not possible by manual control.

All these techniques effectively knock the corners off the square wheel and give the plant a much smoother ride. With a sufficient number of production lines, a producer may be able to devise completely rounded product slates, analogous to perfectly round wheels.

There is little doubt that useful and almost perfectly rounded product slates can be devised for almost any process. This being the case, it is tempting to conclude that grade change characteristics are immaterial to process comparisons. However, as every producer knows, grade changes are always a concern, even with very well rounded product slates (slide 17). No matter how well the slate is rounded, a minimum difficulty with grade changes will always be encountered. This minimum difficulty exists because, regardless of how few grades are included in the slate, a product inventory of each grade must be maintained to avoid stockout penalties. If a plant is assumed to operate with more than one grade, grade changes will continue to require some out–of–the–ordinary operating procedures that cost money to execute. Finally, a minimum run length between changes will be necessary to allow time for widespec product to be backblended into prime product.

It is difficult to visualize a product slate for a process that would have a minimum difficulty rating. From one aspect, the difficulty rating could be decreased by reducing the number of reactor grades, until ultimately only one grade is left. By definition, however, that approach makes grade change meaningless. From another aspect, grade change difficulty could be reduced by making grades that are closer and closer to one another in quality, until ultimately all grades have the same specification. That slate is also meaningless from the standpoint of grade change penalties. However, during our grade change analysis (slide 13), we found that as slates were made easier and easier a tendency for points to "bunch" toward the lower end of the difficulty/penalty line emerged. For example, visual extrapolation of the plot for the gas-phase fluidized bed polyethylene process indicated that it would be extremely difficult to devise a product slate with a difficulty rating of less than about 9 or 10. We found that similar minimum difficulty ratings could be visually extrapolated for all other processes. This point of minimum difficulty and minimum penalty we took to be equivalent to a perfectly rounded product slate for each process. Our analogy with a wheel allows interpreting the location of these points as an indication of the size or diameter of the perfectly circular wheel of each process. No matter how much producers may backblend widespec product or optimize their product slates, they cannot escape the fact that their processes have grade change wheels and that they will always have some grade change penalties related to the size of those wheels.

To compare these optimized penalties for different processes, we plotted all the points on a minimum difficulty/penalty graph and, to our surprise, found that they all could be well correlated by a single parabola (slide 18). In other words, our 800 simulated grade changes had been reduced to a single line. Although this finding was anticlimactic, it was also extremely useful. We have found a somewhat simple method by which processes with vastly different reaction systems can be compared on a directly equivalent basis. The position on the curve gives a direct reading of the comparative grade change flexibility of the process and associated cost penalties. Processes that are close to the origin are the most flexible. As the slide shows, the high-pressure LDPE processes are the most flexible, which is not surprising because of their very short reactor residence times of about 0.5 to 2 minutes. Solution processes are the next most flexible, and in fact one solution process overlaps the high-pressure processes. All slurry phase processes fall in the same region of the curve, and they are all significantly less flexible than the solution and high-pressure processes. At present, gas phase processes are the least flexible processes, and they incur the highest grade change penalties. These processes are the most recently developed polyolefin technologies, and as they mature their flexibility is expected to improve, moving down the curve toward the slurry phase domain. However, it is highly unlikely that slurry and solution phase processes will be able to obtain further significant improvements in grade change flexibility.

The implications of this grade change flexibility curve are broad (slide 19): In addition to allowing the direct comparison of processes on a uniform basis, the curve provides the means for estimating grade change penalties for any rounded product slate from any production process by adjusting the position and shape of the curve. It is easy to adjust for changes in the interest rate on working capital, as well as for variations in the price delta between widespec and prime product, and for changes in local chemical industry cost conditions (e.g., plant construction cost index and the cost of labor and energy). Because grade change penalties can be estimated for any product slate, it is possible to conduct a meaningful analysis of the multistream option for plants having a broad product slate. Finally, with a knowledge of grade change characteristics production schedules can be optimized for the best process/market fit, giving production managers full control of their competitive positions.

Slide 1

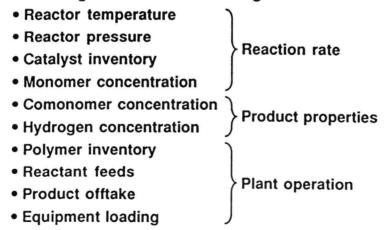
GRADE CHANGE = MANAGER'S HEADACHE

- Each change disturbs steady plant operation
- Changes increase risk of shutdown
- Changes must be planned to:
 - Maximize product range
 - Ensure ready availability of each grade
 - Minimize product inventories
 - Minimize "widespec" productMaximize annual production.

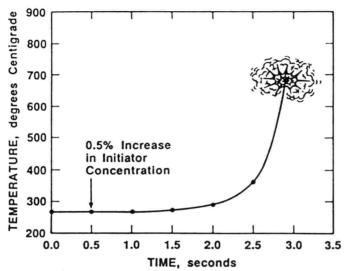
Slide 2

TESTING THE OPERATOR'S LIMITS

Grade change = simultaneous changes in:



Slide 3
HIGH-PRESSURE AUTOCLAVE LDPE PROCESS
REACTOR RESPONSE

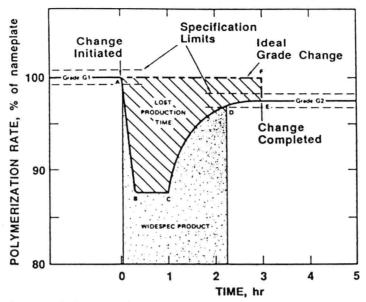


Source: SRI International

Slide 4
ASPECTS OF GRADE CHANGES

- Production must often be slowed to maintain safe operating conditions.
- Product made during the transition is of intermediate quality ("widespec") and must often be sold at a discount.
- An inventory must be kept of each product grade. Inventories are financed by working capital.

Slide 5
GRADE CHANGE SCHEMATIC



Source: SRI International

Slide 6
A TYPICAL PRODUCTION CYCLE

