PRESENT STATUS AND FUTURE NEEDS - A VIEW FROM NORTH AMERICAN INDUSTRY

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Abstract. This paper presents an assessment of the process control community from the viewpoint of a large American chemical company. Recent changes in the definition of and customer expectation for product quality have directed the industry's awareness to the importance of product consistency. A change in attitude from "quality means high purity" to "quality means low variability around a specification target", implies new opportunities for the process control community. This paper discusses our current status and suggest some future needs for the process control community in light of current attitudes toward quality.

Keywords. Control Strategy; Education; Process Design; Quality; Statistical Process Control; Process Variability

INTRODUCTION

Over the last several decades the American petrochemical industry has changed from one of leading the world in technology, innovation, and process operation to one being driven more and more by external forces beyond its control. Once characterized by product variability, cheap energy, and production capacity, it has become an industry where the manufacture of consistent products using minimum energy and creating little waste are now key elements.

The quality revolution which started in the consumer products industries has now reached into the supply chain not one but several layers deep. This demand for increased consistency in the properties of products supplied by the chemical industry has led to decreased sales and lower prices for those companies not conforming to customer demands. In times past, companies could use additional energy to over-purify or rework out-of-specification material. Now companies can no longer rely on making products better than specification to achieve sales volumes. The market now demands that products meet criteria related to product variability in addition to purity specifications. Today low quality is synonymous with high variability in addition to not meeting purity specifications in an absolute sense. The demand for product consistency is only going to become greater. In ten years the ability to produce highly consistent product will not be an issue because those companies that fail in this effort will be out of the market or possibly out of business. Among the remaining companies, the central issue ten years from now will be the efficient manufacture of products that conform to customer variability expectations (Doss, 1990).

This trend has brought to the attention of corporate management the need to address the issue of making "quality" products in addition to meeting sales and earnings goals (Block, 1990). People possessing fundamental knowledge of managing process variability, *those in the process control field*, for the most part have not been sought out to solve quality problems. However, those in the process control field are the very people best able to solve the variability problems that result in poor quality (Kirby, et al. 1990).

Achievements in the discrete parts manufacturing industries using statistical process control (SPC) have turned the eye of American management to SPC methodology to address the quality problems in the continuous process industries (Moore, 1990). The industrial engineering community thus far has been the primary source tapped to attempt to lead the continuous process industries out of the quality dilemma. The tools in the industrial engineers' repertoire for attacking the problems of product consistency are statistics, design of experiments, human factors, and in particular SPC. The SPC guru generally treats a complex chemical process as a statistical black box and as a result only treats symptoms of the underlying problems. Process understanding that is invaluable when developing cost effective solutions to cure the problems is not involved. The SPC practitioner is not trained to conceive of solutions that involve as little as a plumbing change. Simple solutions such as run charts have been used effectively in some cases. However, for many problems this type of approach leads to confusion and frustration because the dynamic nature of the process is omitted from the picture.

The fact that the process control community has not been sought out *first* to solve process variability problems is an indication that either the skills of the process control community are not recognized, or that we are perceived as not being the best ones to address the need. We must look at why those with few and relatively simple tools are receiving not only support from corporate management but also grass roots accommodation of SPC from the engineers in plant operations. Our concern is that the SPC community is attempting to provide solutions to variability problems that are in fact process control problems, and they are succeeding -- not in solving all the problems but in the acceptance they are receiving. This apparent success has raised some fundamental questions of how well we in the control community are providing the solutions to current industrial needs (Moore, 1991).

We feel the reason control engineers are not in demand is that a trend toward generality has moved process control away from chemical engineering and toward control theory. As we become more abstract, our technology is being understood and applied by fewer and fewer chemical engineers.

Contrast for example the language used by the control community and the SPC community:

SPC Community	Control Community
quality	discrete convolution model
customer linkage	poles and zeros
process improvement	structured uncertainty
dollar value	covariance matrix

From the point of view of the production engineer, marketing expert, production supervisor, or plant manager, the language of the process control community sounds quite foreign and intimidating whereas that of the SPC person sounds familiar and appealing. Within our community there exists the capability to discuss control theory in many complementary languages such as the time domain, the "s" domain, the "z" domain, the impulse response domain, etc. Our ability to communicate internally is a crippling disability when it comes to communicating and selling our ideas to others. We hinder our acceptance with plant personnel when we resort to "jargon escalation" -- in a theoretically correct attempt to effectively capture and describe mathematical nuances, we quickly lose our intended audience and our eventual customer.

The trend of the process control community away from the solving of specific chemical engineering control problems to the developing of control theory has resulted in our not being in the main loop of quality improvement programs which are aimed at variability reduction (Moore, 1990). We believe that there are three main areas that are in need of change:

(1) movement away from control algorithm development toward control strategy development,
(2) movement away from "process design *followed* by control system design" toward an integration of process and control system design, and

(3) movement away from teaching control theory toward more inclusion of teaching how to control processes.

In this paper we explore these three main issues by examining their current status, defining some future needs, developing an example, and discussing what we do at Tennessee Eastman to address each issue in our own situation.

CONTROL ALGORITHM DEVELOPMENT AND CONTROL STRATEGY DEVELOPMENT

Current Status

The ability to design and develop control algorithms is one of the control community's strengths. When given a process model, in particular a linear process model, it is possible to design automatic control algorithms to make the model behave in about whatever way we desire. Likewise, if there is a fundamental response limitation, for example an inverse responding process, that limitation can be quantified as well. For nonlinear processes, processes that change over time, and unstable processes, a good deal of theory and design methodology exist to address these issues as well (Luyben, 1990; Seborg, 1989; Stephanopoulos, 1984).

Advancements have been made to clarify the effects of assumptions made in our modeling efforts. Technology advancements are being made to quantify model uncertainty for linear systems and to give indications of what uncertainty is the most critical to design (Morari and Zafiriou, 1989).

Great strides have been made in the development of algorithms which can take into account process constraints and process optimization opportunities (Prett and Garcia, 1988). The advent of model predictive control algorithms has led to the incorporation of current and future constraints into the control algorithm itself (Cutler and Ramaker, 1979; Mehra, et al., 1982). These algorithms have the capability to take into account the interactive nature among many controlled and manipulated variables. In addition, the predictive capability is very amenable to optimization over future time horizons as well as current operation. Several companies have been formed to exploit these developments and we hear about great successes in applying their algorithms (e.g. Lane, 1989; Rhemann, et al., 1989).

These developments are impressive but only address the control algorithm part of the process control problem. Control algorithm design frequently assumes that the process measurements and control valve locations are fixed, whereas the industrial control problem is seldom limited by these constraints. When focusing solely on control algorithm design, the chemical engineering aspect is absent.

Current academic reward systems focus attention on control algorithm development and not on process based control concepts. The academic emphasis placed on generality has nearly eliminated case study methodology that includes the specifics of a particular process. The path to archival publication is to develop an algorithm that can be applied to any system (chemical processes, electrical networks, mechanical robots, etc.) that follows a given model structure, often linear, and then to embellish the algorithm to define its limits and extend its applicability to special subclasses. The actual application to determine how well the algorithm satisfies the many objectives of process control is only assumed based on mathematical prediction. There is little process understanding or process emphasis at all. One only has to look as far as the volume of work done in the distillation control area to see that when an actual unit operation is considered, the insight into the process itself has much to do with control system development. In fact, understanding of the distillation operation is the theme that differentiates distillation control developments from their more generalized counterparts.

Future Need

We routinely encounter opportunities for process improvement by means of control strategy changes. By control strategy we mean: (1) control system objectives, (2) the selection of sensor type and location, (3) valve type and location, (4) input/output variable pairing for SISO structures, and (5) decentralized control structures for multivariable control. Technology for the design of control strategies broadens our domain to also include changes in the processes we are controlling.

At the heart of control strategy design is the ability to look at the process control problem as one of transforming variation from one point to another by the control system. The real purpose of a process control system is to shift variability in one part of a process to a less critical location (Moore, 1991). Depending on the control strategy, there may in fact be a need for an advanced algorithm to push variation into certain places. However, the point is that *where* the advanced algorithm is needed has been overshadowed by the design of the algorithm itself.

With the current emphasis on algorithm development we seem to have lost sight of the process and as a result many control issues are overlooked as well. Using process understanding, we believe that good, first level, SISO based control strategies can be developed that incorporate additional issues beyond controller performance. We can begin to address questions such as:

(1) Where in a process are the effects of raw material variability going to manifest themselves?
(2) How will environmental variability be propagated through the process and will it affect the final product?
(3) What is the tuning objective for each control loop -- loose control or tight control?
(4) What is the costs versus benefit comparison for one control strategy versus another?
(5) How difficult will a control strategy be to maintain after those who designed it are gone?

(6) Is the intent of the control system understood by those who will have to use it, namely production engineers and plant operators?

Technology for the design of control strategies from a process point of view is very limited. Control strategy design requires a plant-wide perspective and encompasses issues in addition to the control algorithms to be used. We believe that the development of a comprehensive set of case studies to help understand the tradeoffs of different control strategy design approaches is needed to help develop control strategy design technology (Downs and Vogel, 1990). We believe that we must begin to answer questions such as those listed above in addition to algorithm design to fully exploit and apply our talents.

Example

The influence of the process on control system design is illustrated using the reactor feed preheater shown in Fig. 1. From a process point of view, the control system relocates variability in the feed exit temperature to variability in the hot stream flow rate. As the control algorithm and/or the controller tuning change, different amounts of the variation are transformed. Depending on the process it may be more desirable to have all the variation in the flow rate of the hot stream (tight control) or all the variation in the feed exit temperature (controller in manual or no control at all). The control algorithm gives us the freedom to adjust the amount of inlet temperature variation that is shared between the outlet temperature and the hot stream flow rate. However, understanding the objectives of the process are critical to the design and tuning of the controller. The use of advanced control techniques such as an adaptive controller or a nonlinear controller may be warranted for tight control of the reactor feed temperature, but we would never know unless we understood what the process objective of the exchanger was in the

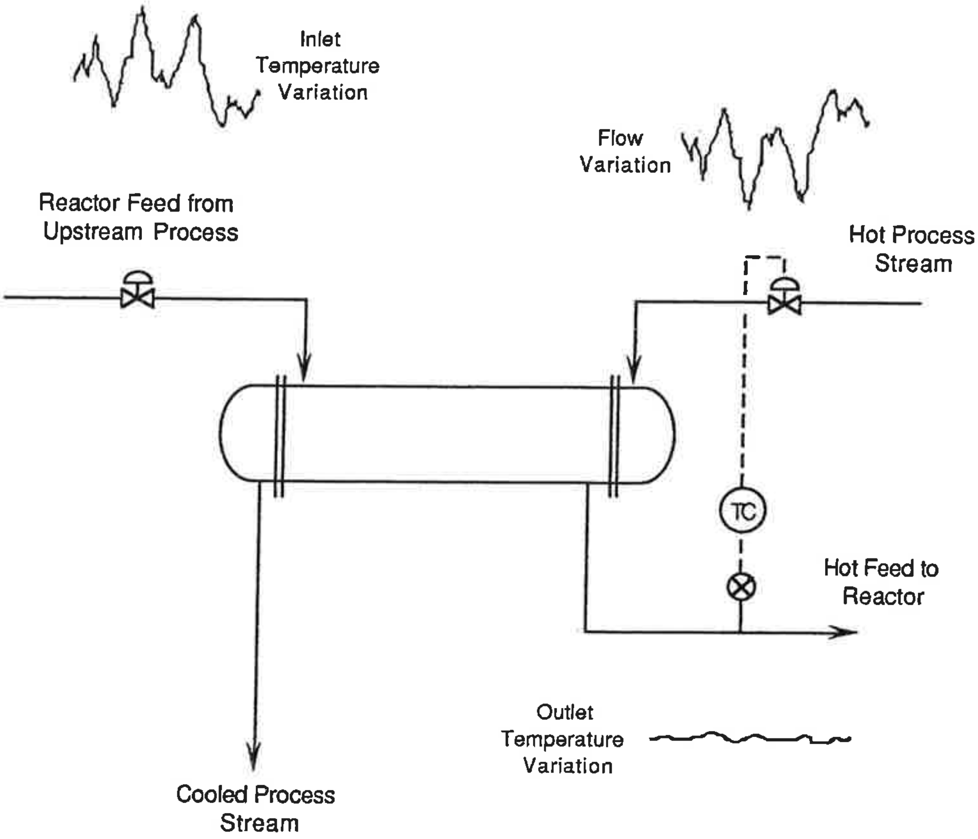

Fig. 1. Transformation of variation from temperature to flow for a reactor feed preheater.

first place. The tuning objective is an example of a process driven question for which responsibility has been abdicated.

Control strategy design broadens the control issue to address relocation of process variation such that it will be least harmful. This focus brings attention back on the process rather than on the control algorithm. If the process containing the heat exchanger in Fig. 1 demands *both* low variability in the reactor feed temperature *and* in the total flow rate of the hot process stream, then a simple process modification such as the bypass stream shown in Fig. 2 may be a solution. The bypass allows the inlet temperature variability from the upstream process to be transformed to variability in the outlet temperature of the cooled process stream. The control strategy design, the selection of a bypass and three way valve for the manipulated variable in this example, determines the places available to assign the location of variability. The best control for the outlet temperature is determined by process issues and not by what algorithm we use.

At Tennessee Eastman

Our approach to the design of control strategies has been to develop a fairly comprehensive dynamic simulator (Downs and Vogel, 1985; Vogel, 1991). It allows us to poke and prod a process from varying perspectives and to understand the dynamic problems and hence the control problems. From there we can design the control strategy or change the process. Steady state analysis tools such as relative gain array, block relative gain array, and singular value decomposition (Bristol, 1966; Downs and Moore, 1981; Manousiouthakis, et al., 1986) are among the currently implemented tools we use. These tools help us evaluate and screen our designs but are limited in that they are only analysis tools. Dynamic simulation allows us to compare behavior of possible control strategies and assess the propagation of variation through a process.

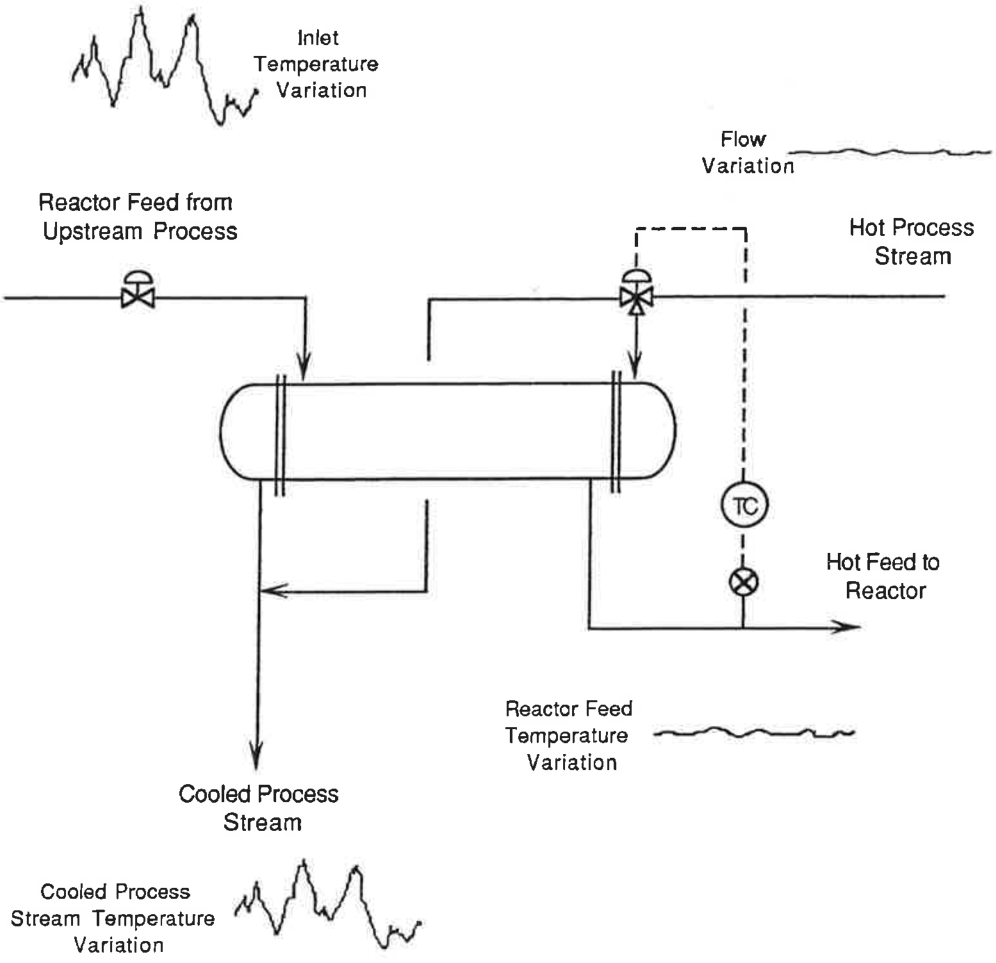

Fig. 2. Transformation of variation from one temperature to another temperature for a reactor feed preheater.

PROCESS DESIGN AND PROCESS CONTROL

Current Status

The single word that describes the routine interaction of control system design with the process design is "afterthought". A procedure in many engineering design firms is to design a process that utilizes the novel process chemistry or processing techniques and worry about the design of the automatic control system later. Usually "later" means after the equipment layout and process design are fixed. As a result, even base level regulatory control strategies may become complicated and unwieldy. Often during startup, control strategies are changed just to get the plant up and running. This ad hoc approach in turn results in piecemeal installed control strategies which yield low quality product (high variability), difficulty in optimizing plant operation due to varying process conditions, and an impression of a need for advanced control schemes. If the problem stopped here it might be tolerable. However at this point, enter the SPC gurus to "solve" quality (i.e. variability) problems. The array of Pareto diagrams, run charts, and brainstorming sessions seem to cost about as much as the off-specification product itself. Often with even a small amount of dynamic perspective at the design stage, one can avoid this entire scenario.

When viewed on a project time line, the tasks of process design and control strategy design are usually arranged in a sequential fashion rather than a parallel one. The location of the process control group (if one exists) may be organizationally and geographically removed from the process design group. The fact that process control technology is steeped in algorithm development gives rise to an attitude of "you design the process and I'll figure out a way to control it using the many algorithms in my bag of tricks". This approach promotes a notion that *any* sacrifice of process design optimization in the name of process control or operability is an admission of weakness and is not cost effective. In addition, with the process control focus on algorithm development, the mission statement for the control group reads something like "Given a plant ..." with valves and sensors already in place. With this attitude, the opportunities for better control through better designs are missed. With input at the design stage, the plant design is definitely *not* "given" and is an integral part of the control strategy design.

Future Need

There is a need for technology that links the process design with the control strategy design. The integration of these two tasks at the process design stage can have great impact by designing away process control problems. By designing processes that inherently eliminate variability or have "variability sinks", we can manage process variation and improve the quality of our products. We have at our disposal flowsheet modifications, strategically placed process inventory, or other process shock absorbers that can be used to handle process variation. The incentive here is that a docile process that can be well controlled and operated by a basic PID based SISO strategy will require little in the way of training and maintenance. On the other hand processes requiring special, complex, and fragile control schemes tend to need constant attention and nurturing to ensure continued use and benefit. There are many control problems that can be designed away for little economic cost. We should correct the control problem at the source rather than treat the symptoms of a bad design using advanced control.

To achieve the elimination of control problems at the design stage, we believe that the process design and process control design groups must be linked. Technology that links process design and control system design could lead to the concept of self regulating plants and self optimizing plants that do not need complex algorithms for control and optimization. Flowsheet design for dynamic operability and management of process variation is a big opportunity.

We can summarize the relationship between control algorithm, control strategy, and process design with the following overall view of integrated process *and* control design.

(1) Control algorithm design sets the amount of variation transformed.
(2) Process control strategy design sets the path that variation will take through a process.
(3) Process design can eliminate sources of variation and create new paths for directing variation.

With this broader view of "control", we can manage process variation with all three approaches. Our efforts to date have only focused on the first aspect, algorithm design.

Example

An example of building a control problem we used to see often is the specification of an internal condenser on distillation columns having many trays as shown in Fig. 3. During the equipment design phase, a mandate to minimize capital costs is not uncommon. The column designer can see cost advantages to eliminating the reflux drum, reflux pumps, level control loop hardware, vent piping, purge and measurement hardware, etc. After an economic analysis is made to determine the savings, a decision is made to eliminate the reflux drum. To the equipment designer the need for the reflux drum for control reasons is not readily apparent. The plant design continues and equipment layout and structural steel designs do not account for the possibility of a reflux drum and all its associated dressing. The control engineer is then asked to check the piping and instrumentation diagrams which includes the process control strategy. (Note that the original strategy may or may not have been developed by a controls engineer. In fact the first pass may have been put on by draftsmen based simply on their previous experience.) At this time the control group will look at the unit operation control and

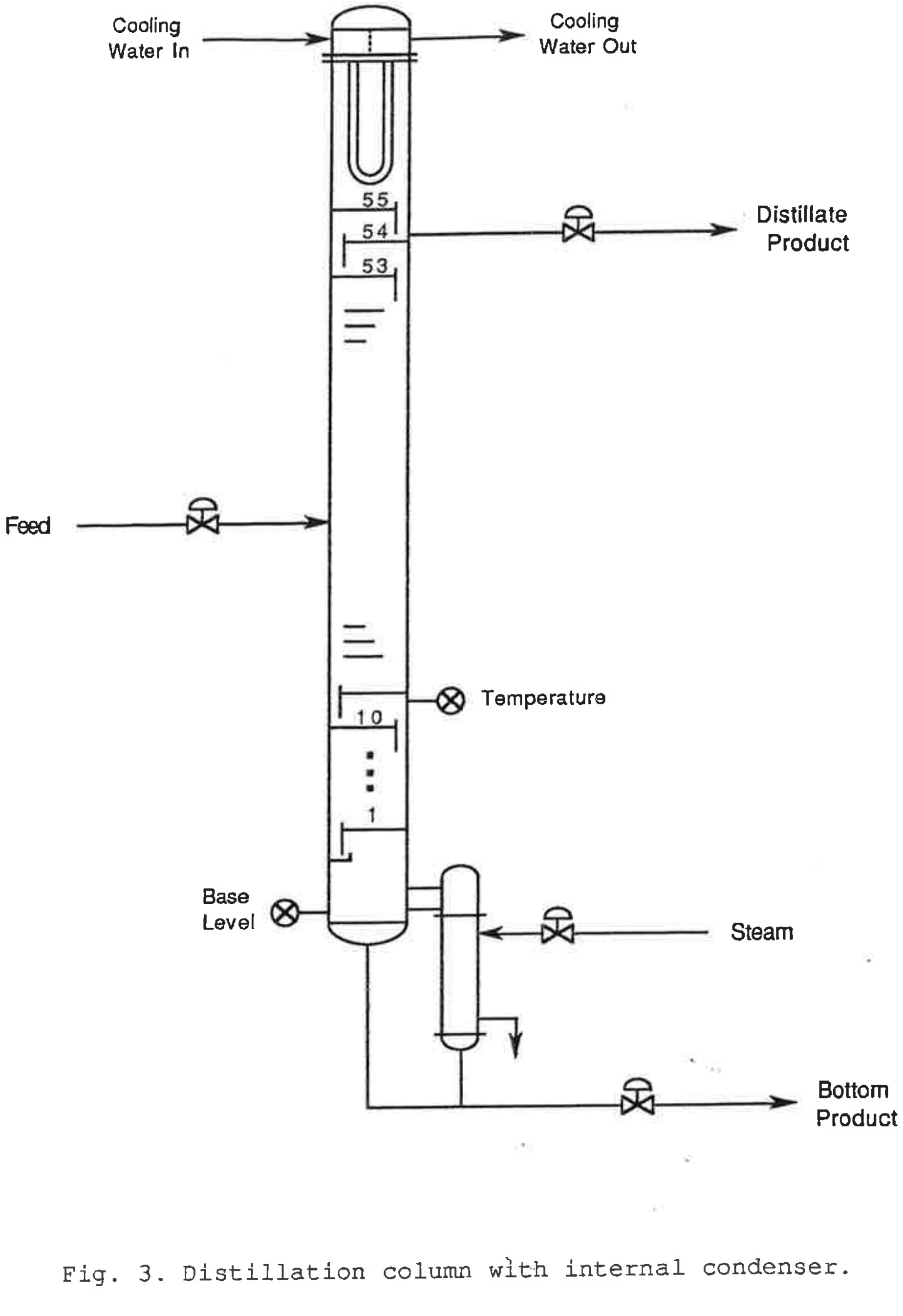

Fig. 3. Distillation column with internal condenser.

begin analysis of the control for the column with the internal condenser. They discover that single point temperature control is sufficient and that the temperature control point should be in the stripping section 10 trays from the bottom for the 55 tray column. At this point the design flaw is understood. The control engineers then realize that they are either locked into a direct material balance control scheme with the distillate valve being used to control tray 10 temperature, or they attempt to develop a complex strategy to tie the distillate rate to low boiler inventory. Either way the control will be fragile and relatively poor when compensating for feed composition disturbances. They must now go back to the designer and state the need for an external condenser/reflux drum arrangement which costs dearly in terms of project rework and schedule delays. Should this recommendation be rejected, the column is destined for a lifetime of poor service. Control theory by itself does not lead to the best solution in this example.

At Tennessee Eastman

At Tennessee Eastman one of the key strengths has been the day to day interaction among the process design and the control system design people. Geographically, these people are housed on same floor and in the same office area. Organizationally they are in the same department and are linked by a common computer network. This proximity has helped promote the interaction needed to ensure that the new processes we design, as well as retrofits, are well thought out from both a process *and* control point of view. However, this proximity has in no way precluded our need for technology to design plants that are optimum from both steady state and dynamic viewpoints.

PROCESS CONTROL EDUCATION

Current Status

The educational system teaches process control from a very general perspective. This perspective focuses attention on the application of control technology for any "system", not necessarily a chemical process. This perspective provides a good fundamental understanding of basic control theory but omits the connection with chemical engineering. Imagine teaching heat transfer by stating the energy balance equation from Bird, Stewart, and Lightfoot (1960) but never addressing the issues of uncertainty in heat transfer coefficient correlations, fouling, poor physical properties, etc. In other areas of chemical engineering we teach the fundamental principles and then follow up with the application to the specific design of a piece of equipment. In process control our specific designs consist of algorithm design for the "model of a distillation column given by the following transfer function ..." The inability of B.S. degree engineers to sketch basic control strategies for common unit operations points to this problem. They have never had to decide what to measure or what to manipulate for control of a unit operation, only what algorithm to use once those decisions were made. We routinely have requests from engineers in our plant operating areas for the teaching of process control basics. These requests include loop tuning techniques, development of alternative process control strategies, and descriptions of the difference between a time constant and dead time.

Graduate education courses in process control are taught with the assumption that the student has mastered the material described above. If this assumption were the case, the current graduate programs in process control would be more effective. The study of control theory by the graduate process control specialist is appropriate. However, with the above material not being taught well, the graduate process control specialist begins to believe that the advancement of control theory is the key issue needing to be addressed. The well defined mathematical problem statements suggest universal answers and are appealing to the mathematically inclined student.

Graduate research directions in the academic process control community are also moving further and further toward control theory. We believe that this trend is being driven by two main forces. First, the desire to obtain grants and to publish papers has led research efforts to appeal to those who approve such grants and review such papers. For a review system only looking for new mathematically intensive developments, there is no room for the issues of how one actually applies the latest technology. The reports of how control is applied and the pitfalls encountered are considered only for trade journals and seem to be considered of little value in the advancement of the science. Case studies to evaluate ideas and methodology are few compared to the wealth of papers stating what can be achieved using some particular method on a linear model. Second, the desire to work on technology that is well defined and mathematically tractable has led to research that is very elegant in terms of the mathematical structure but that is often too far afield and containing too many unrealistic assumptions to be incorporated into practice from an industrial point of view.

Future Need

Undergraduate education needs to equip B.S. degree engineers with the fundamental concepts of process dynamics and its interaction with process variability. The undergraduate engineer who is in a production environment is geared toward finding simple, workable solutions. He is rarely involved with the analysis of control loops or the design or application of advanced control algorithms. He *is* faced daily with the need to understand that all his processes are dynamic and that they move with time, that the control strategy determines the path variability will take through his process, and that the tuning on each controller is determining how much variability is being transformed. He usually learns well the processes for which he is responsible and knows their unique control problems. What he needs is a base level understanding of differential equations, process dynamics, dynamic modeling of basic unit operations (in the time domain), basic control algorithms (such as PID), cascade structures, and feedforward structures. With these basic tools and an understanding of how to apply them, he can solve most of his control problems himself. What he does not need is the theory and mathematics that usually surround the teaching of process control such as frequency domain analysis.

Understanding of dynamics coupled with knowledge of unit operation design would lead to teaching unit operation control and the concepts of transforming process variability and the role played by the control strategy. Case studies of simple unit operation control would give the B.S. degree engineer a basis for understanding and evaluating control strategies when he joins industry. Case studies would allow students to learn how to apply the theory. With an understanding of process dynamics, basic control algorithms, and his knowledge of the process, he would be in a position to often solve his own control problems and be able to know when to call the control specialist for help.

Graduate education in process control is the place to introduce frequency domain concepts and expand process control strategy design to a plant-wide scope. A Masters level chemical engineer should be able to sketch a first level control strategy on a process and rank the loops in order of difficulty. He should also understand dynamics well enough to write a time domain dynamic model of typical unit operations. Advanced control mathematics, algorithm development, nonlinear control, and adaptive control would be taught to those specializing in the process control field. We believe strongly that the chemical engineering control specialist should be well versed in the science of control algorithm development and the mathematics that go along with it. The doctoral level engineer should be able to understand the science and be able to contribute to its advancement.

In summary, we are not saying to throw the baby out with the bath water and eliminate frequency domain analysis and advanced control techniques altogether, but simply to leave these topics for the control specialist and as electives for those interested. A basic understanding of unit operation control and simple process dynamics will go much further toward equipping future engineers to solve the day to day control problems that contribute the most to product variability and consistency problems.

Example

Consider the teaching techniques we use for plant design. When an undergraduate reaches the plant design course he has to become focused on specific plants. He can no longer refer to mathematical abstractions to describe the issues associated with a design. The designs become specific case studies to examine the pros and cons of design decisions. The engineer learns by example how to use engineering judgement and experience to influence decisions.

The senior design course at The University of Tennessee was taught for many years by Professor Oran Culbertson. His technique was to select a hundred processes from *Hydrocarbon Processing* and lay them face down on a table. On the first day of class each student would select a piece of paper containing a process. There were no duplications so each student had his own process. His job was to design the equipment, determine capital and operating costs, and determine economic viability of his process. There were no generalities, only specific examples that each student had to worry about himself. Each case study provided the avenue for the student to learn the issues that crop up when one actually attempts to apply the theory one has learned. Process control needs to incorporate this spirit of application. This kind of approach helps focus attention on the process rather than the algorithms.

Contrast the educational paradigm in the process control field with that in the medical, legal, and business professions. These professions have a frequent emphasis on case study methodology. Their educational paradigm is taught by those who have practiced what they are teaching and can be summarized as:

(1) present a single illustrative case,
(2) abstract lessons from the specific to the general, and
(3) iterate (1) and (2) such that there is a gradual buildup of an overall abstract knowledge base supported by hundreds of case studies.

The educational paradigm in the process control field is often taught by those who have never practiced or have limited experience in the field and can be summarized as:

(1) start with a purely mathematical description (abstraction),
(2) develop, analyze, and evaluate theoretical descriptions, and
(3) apply the theory to specific abstractions. (e.g. "For this transfer function design a controller ...")

While this approach has much scientific appeal, the ability to *transition from the abstract to the specific* is not taught along with the study of the mathematical abstraction. We never learn how to apply the tools. The art of using process knowledge, simulation, and process dynamics is missing.

At Tennessee Eastman

The concept of gaining understanding by looking at case studies is illustrated by an internal follow-up program we use to help us track the performance of our control group's work. It furnishes feedback on how well we are doing at providing process control technology to our customer. We are normally present during process checkout and startup to ensure proper control strategy commissioning. In addition, for each loop we commission which requires some special or extra design and thought (liquid flow, reflux drum level, etc. not included), we follow-up 1, 3, and 6 months later to determine if the loop is still in automatic and performing its intended function. The knowledge gained from particular applications is fed back to the control group as additional support for future projects. We find that if the strategy is not working as commissioned, the reasons are seldom technical ones. Usually ancillary issues such as operator understanding, startup and shutdown issues, measurement problems, or other related process problems are the culprit. We find that if all these issues, not just the technical ones, have not been addressed, the best technical solutions become worthless and the resulting control solution is abandoned.

This "pull-through" of plant experience is invaluable to the improvement of future designs. It provides the feedback we need to keep our internal research and development efforts focused on problems that need to be solved in the short term and provides the basis for our long term research directions.

CONCLUSION AND RECOMMENDATION

We must break out of our educational, research, and industrial thinking paradigms that are blinding us to the needs of the American petrochemical industry. At one time it was believed that the American steel industry was second to none in quality and productivity similar to current beliefs about the American petrochemical industry. We must not deceive ourselves into believing that somehow we are different. The current quality of our products will ultimately be our demise unless we are effectively exploiting our vast process control knowledge.

We believe that the pendulum must swing away from control theory and toward chemical engineering. We must develop technology and chemical engineering graduates who can help the continuous process industries design processes and control strategies that work in concert to continually improve product quality.

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