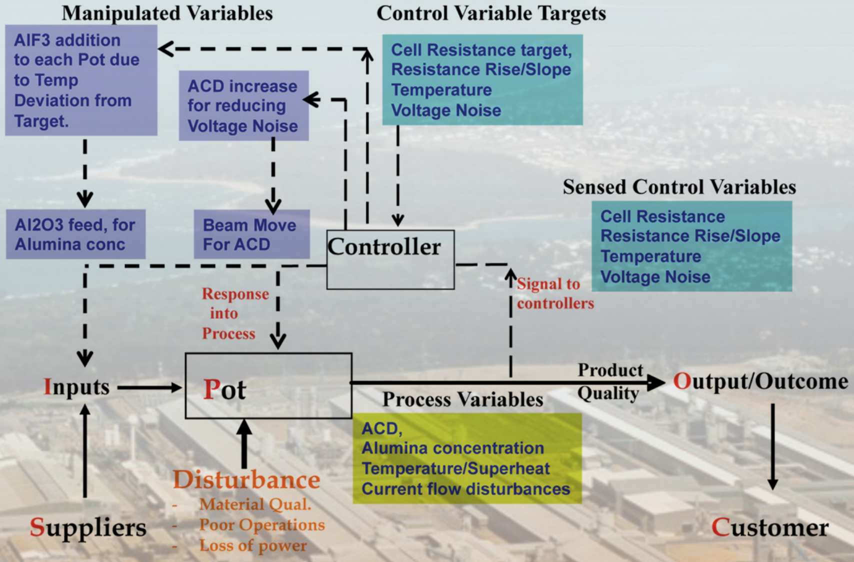
CONTROL for ALUMINUM PRODUCTION and OTHER PROCESSING INDUSTRIES



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Preface

The genesis of this book lies in the history of process control achievements of several aluminum smelting plants, in particular, New Zealand Aluminium Smelters Ltd and Boyne Smelters Ltd. Many of the people who worked at these plants in the 1990s have contributed since to the events and hard-won insights about control that the authors have set out here for the production and materials processing industries.

From 2002 until the present day, the authors have been engaged in industrial plant improvements with many companies in Australia, the United States, Canada, United Arab Emirates, Bahrain, Norway, Netherlands, Germany, France, Malaysia, South Africa, Russia, China, Japan, and New Zealand. The control experiences of these organizations, both good and bad, have provided additional insights on not only what can go wrong but also what is needed to turn these situations around and prevent them from reoccurring.

An uncomfortable but unavoidable statistic in the shift logs and process control records of most plants the authors have worked with is that many process control failures, large and small, happen every day in complex production processes. Only a small fraction of these failures give rise to catastrophic events that are then reported in the media. The difference between a disaster one reads about and a failure that is expensive, but has no irreversible consequences, is, again, uncomfortably only chance.

It also is well established that people tend to learn only through failure, and most often their own. The characters in the production plant described here will undergo the *real world* journey in which there are more control failures than successes, and in which control is not a given but something that must be strived for every day. It is hoped that production people everywhere, and students of production processes, find these control experiences both familiar and a basis for building their own personal framework for how plant control problems can be resolved and avoided in the future.

The authors thank Keith Sinclair, Tony Aldridge, and Barry Sadler for their insights before and during the writing of this book. We also acknowledge Steve Lindsay and Halvor Kvande for their encouragement to do it, as well as Florence Taylor for her artwork in the drawings and diagrams. We also are indebted to the staff of the Light Metals Research Centre at Auckland and the smelting industry in its entirety for providing such rich experiences on which to base the practical lessons contained within.

About the Authors

Mark P. Taylor, PhD, CEng, FIChemE, has spent 20 years in technology development and line management in heavy industry, in primarily aluminum production and related businesses. During this time, he has worked at the interface between research and production to create higher value products, reduce energy and materials consumption, as well as manage implementation of projects such as the $500 million expansion of the Tiwai Point smelter, which lies on the southern coast of the South Island of New Zealand. Dr. Taylor was subsequently potroom manager at Tiwai Point and general manager of operations at Boyne Smelters in Queensland, Australia.

In 2003, he joined the University of Auckland as founding director of the Light Metals Research Centre, which has since become a world leader in research applications in practice. In 2012, he received the TMS (The Minerals, Metals & Materials Society) Application to Practice Award in the United States for his applied research in the industry.

Professor Taylor now serves as director of the Materials Accelerator that he co-founded with Dr. Ralph Cooney in 2009. The Materials Accelerator is a national network that partners with key research providers including AUT, VUW, Massey, UoW, Scion, GNS, UoA, and UoC to create export value for many New Zealand companies, both small and large.

Brent Young, PhD, BE, CEng, FIChemE, is a professor in the Department of Chemical and Materials Engineering at The University of Auckland (City Campus). He holds the position of chair in food process engineering and is director of the Industrial Information and Control Centre.

Dr. Young was previously an associate professor of chemical and petroleum engineering at the University of Calgary, Alberta, Canada (1998–2005) and a lecturer in Chemical Technology at the University of Technology, Sydney, Australia (1991–1998). He also has held prestigious visiting positions including NSERC (Natural Sciences and Engineering Research Council of Canada) at Calgary (1995), an Erskine at Canterbury (2005), and a Gledden at Western Australia (2009).

He earned his BE (1986) and PhD (1993) degrees in chemical and process engineering from the University of Canterbury, Christchurch, New Zealand. He is a registered professional engineer, a Fellow of the Institute of Chemical Engineers (United Kingdom). He has co-authored over 200 refereed publications, including the book *A Real-Time Approach to Process Control,* 2nd ed. (John Wiley & Sons, 2006).

John J. J. Chen, PhD, BE, CEng, FIChemE, FIPENZ, FRSNZ, is a Fellow of the Institute of Chemical Engineers (United Kingdom), the Institute of Professional Engineers New Zealand, and the Royal Society of New Zealand.

He has served on the TMS Light Metals Division Council and the Aluminum Committee. He has worked in an aluminum smelter for 3 years, and has been an academic for 33 years, with 8 of those (1996–2004) as head of the Department of Chemical and Materials Engineering, University of Auckland (City Campus). He has published over 270 papers in international journals and conference proceedings, and over 60 proprietary technical reports. He has won the Best Reduction Technology Paper Awards at TMS in 1992, 1993, and 1996. His current research covers a number of areas in aluminum smelting technology.

Dr. Chen's research interests include the modeling of the aluminum smelting process, the treatment of molten metal, and process control in the potrooms. He has been for many years at the forefront of multiphase flows and related transport processes. His research team was the first to quantify the impact of bubble-driven flows on current efficiency in aluminum smelting cells and the first to identify and measure the increase in sidewall heat transfer coefficient opposite the bath/metal interface due to the waves in the metal layer impinging on the wall.

1

Importance of Control

The car traveled like it knew the way through wide, empty streets and past treed gardens and colorful flower beds. It was not hard to find Lewis Street. No. 161 was a striking white, rough-cast, two-story, which was laid back from the road. A smooth landing in a quiet smelter town, far from the research center and the city lights.

The general manager had asked, in an airport interview three months ago, why he wanted this job. "You're a researcher, not a production guy. What makes you think it's for you?"

"I've had a lot to do with the plant, John. Working onsite is what I enjoy most. I think I might be a production guy coming out of the closet," an answer that made the plant manager smile—no mean feat, as it turned out.

The truth was there, of course, but not all of it.

Rob did want to work in production. It had fascinated him that people could do work this complex, yet make it simple, and make it last for years; whereas he often got bored by jobs that lasted more than six months. Beyond this was something he didn't understand … the pressure of production written on the faces of managers at all the aluminum plants he had visited, including downstream manufacturers.

What was it? What made the pressure? Rob could see what made it fun, having done it for short periods in assignments to plants that were (meant to be) research programs. The interaction with people, the things that happened in production, making decisions, and taking action fast. Like being in an action movie, but with consequences, Rob thought.

But, what made production that difficult? Producing the same products each day, with the right equipment and guys who knew the process like maps of their own homes. Of course, there were challenges, such as costs and production targets. He was up to that.

Control of Production

Rob Johnston took his dusty, yellowed Edwards Deming seminar notes[1] out of one of the boxes in his new home and remembered, without reading, the voice of Deming during the first day of that seminar:

> Control of production is not concerned with computers and automation. It is concerned with the daily work of people, and everything that happens during it. The quality and cost of your product is all that stands between your factory, and substitution by another factory's product,

> or by another material entirely. Quality is what the customer will pay for. It is also an expectation, and sometimes an excitement. Would you rather make things people love, or need, or just use? And is that product quality consistent day to day?”

Why is the iron content of primary aluminum from one plant 50% lower than that at all other plants using the same raw materials? And will it stay lower? The answers to these questions cannot be found in the ingots and billets themselves. Each piece of data that is spoken or written comes from a process that has variation and has both a location (a mean or median value) and a distribution (range or standard deviation).

You must understand both the location and the distribution of data to answer these questions. Go to the factory floor and talk with the people who run the potlines and the pots themselves. Is the iron content in the metal at the same low level on all pots? What is the distribution of iron across the pots in a potline? But, that is still not enough. Ask the operator if he knows what the iron content on any pot will be tomorrow, and next week.

If he says, “No idea,” or something similar, it may mean that the variation is not stable or controlled. If he says that it will be in this range or that range, then it is more likely that the variation is stable—a process that is under control. Does this mean that we will like the result in terms of iron content? No, of course not. It may be nowhere near our customer’s expectation. That is determined by the process itself, not the customer. If you require a different result from this process, then you will need to collect and analyze data on the subprocesses controlling iron content, propose a hypothesis to improve them, and test that theory experimentally.

This was where some plant managers present at the seminar had lost the plot. Experiments were not in their vocabulary.

However, Deming’s provocative questions went on, and not only about metal purity:

> You might also ask: Why do some cells use more electricity and others less? Why can’t all cells use the minimum amount required?

The plant managers were now sitting up again. Their production costs were determined largely by electricity and raw material costs, which were both heading upward even as the metal price headed downward.

Deming went on, in his slow authoritative style:

> The control and operational thinking that produce these variable results for you today originated in the industrial revolution and after it, and were probably an improvement over the previous generations. But, the competitive pressure, productivity trends globally, energy price, and environmental pressures on industry have completely changed since the 1970s and 1980s when you were taught at school that everything needs to be kept constant in a chemical plant.

That was when the penny started to drop. Rob was hooked on production, without having been there yet.

It was true that now there was an urgent need for reduced energy input and, therefore, cell voltage, to reduce electricity cost, and even to keep some plants in Australia, New Zealand, Europe, the United States, China, and other countries open. Cell life had declined and needed to be restored for environmental and economic reasons to the 10-year life benchmark achieved with Pechiney's AP18 cells in the 1980s but, in the face of cathode current densities, 20% higher than during the 1980s. Furthermore, the flexibility of potline electricity usage was an increasingly important issue for smelters today, because of the interconnection of country and continental electricity supplies and the adverse trends in availability and price that these interconnections were imposing. Variation in electricity demand across a typical week is exemplified in Figure 1.1 for Great Britain (GB) in 2010.[2]

Electricity demand is highly variable in this chart, with daily peaks and troughs giving almost 50% regular fluctuations and requiring increased use of more expensive fossil fuel generation during the peak periods. Interconnection across continents and renewable energy supplies, such as wind power, only add to this variability and cause the entire electricity grid to be subject to unpredictable factors, such as extreme weather, drought, and power station outages. Demand-side changes, such as electric vehicles, will

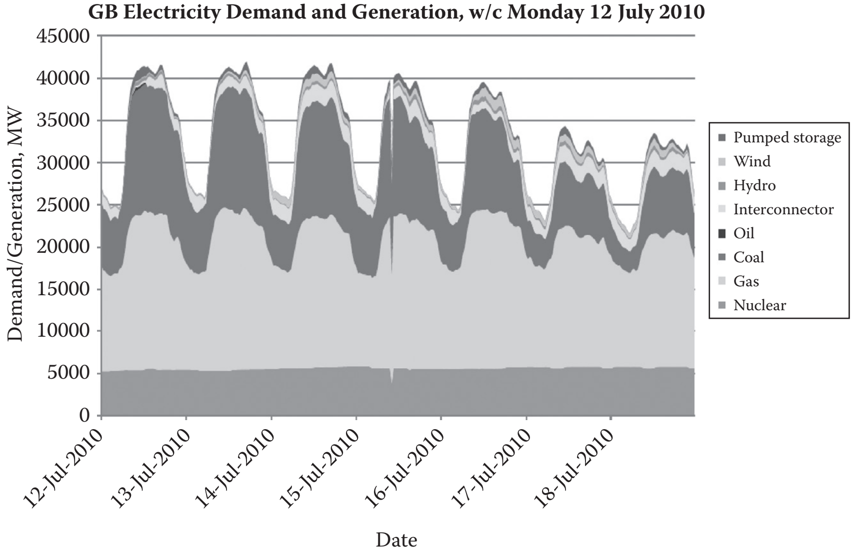

FIGURE 1.1 (See color insert.)
Variation in total power demand and generation during one week in 2010. (Adapted from GB electricity demand variation, pp. 49–53, GB Electricity demand variation—2010 Football World Cup, *Energy Trends*, September 2010, Department of Energy and Climate Change, United Kingdom.)

have an even more profound impact on the magnitude and variability of demand in the future because of the need to charge the batteries of these vehicles at regular times.

In this environment, the availability of large quantities of constant load MW (megawatt) for aluminum production or other industrial outputs is increasingly in doubt in most countries, including rapidly developing ones, such as China, where aluminum production is being moved from highly populated eastern regions to the remote regions of western China. Therefore, it is now essential that industry find flexible ways of producing aluminum and other manufactured products that all require energy, because that energy is not available continuously.

The prerequisite for flexible production of materials, such as aluminum, is a new level of control of the heat and material balance within each production unit. Such control does not exist at the moment, as evidenced by the closure of potlines when electricity price increases or availability reduces. There is, in fact, only about 10% turndown capacity on smelting potlines worldwide before electrolyte freezing or instability renders them inoperable, demonstrating the fundamental lack of controllability of the production process.

Deming went on:

> In this new environment, process control and management failures in production will play a crucial role in factory capability for new products and cost reduction through elimination of waste—in short, the ability of companies to adapt to future challenges.

Rob thought about the visible tip of this "iceberg" of management control failures. There was the heavy cost in pots out of electrical circuit due to failures, anode failures, emissions control failures, reduction of pot life, and low current efficiency periods that his company's smelters had borne on its way to higher amperage, or even just in the course of a normal year. They called these blips "process excursions," he thought with a smile. Like going out for lunch.

The jokes about "excursions" stopped when the average cost of an excursion was calculated to be $25 million. That was one excursion. The cost for the company was closer to $60 million per annum.

The general manager had said, "Well, Rob, you're respected in this plant. I'm pleased to have you on my team."

Now, he unpacked his few remaining pieces of kit and sat in the only chair in the house. Well, it was a start. And, tomorrow was Monday. Southern Smelters in Australasia was at least a familiar place, and Rob knew some of the people, although not many in production. Time for a new challenge. He was in control of production at a major facility.

In control? Well, he liked the phrase, but what does someone do when they are in control? He didn't even know where his new office was. No doubt that problem would be solved. What other ones were waiting? Was that the first prickle of pressure?

Time for a beer, Rob thought, looking in the fridge, the cleanest and emptiest one he had ever seen. Another problem he knew how to solve. Now, it seemed as Rob walked into the supermarket that the problems that worried him were the ones he didn't know about. They could wait for tomorrow.

Rob's mind went back for some reason to the idea of being in control of production. It was happening right now, though. Production. Was he "in control" of it? He thought maybe not … he didn't know whether the process in the potlines was stable or not. And how/when to act if it was not. But, what could really go wrong? And why should it have a noticeable impact on the bottom line? After all, those small variations had always been there, and always would be, he thought.

The Importance of Control in Process and Manufacturing Industries

Recent human and economic losses caused by control failures are not difficult to find. Perhaps the hardest to accept in human terms, involve food safety, where the contamination of the food chain often involves negligence on the part of business people. An example would be the contamination of milk powder in China, in which the Sanya milk powder inputs were not controlled in 2011, resulting in many infant deaths and permanent organ damage.

One difficulty with analyses of disasters such as these is the perception by management that they are isolated events, or that they affect "that company or that industry" and don't apply more broadly and systematically to control of processes. Such myths can be challenged only when companies with the highest reputation for production control also have public control failures. This situation occurred in 2011 when Toyota announced multiple, serious quality failures involving steering wheel spiral cable assemblies (Tacoma models), side curtain air bags (RAV 4 model), and stop lamp switches (Venza, Camry models) over the previous three years, all requiring vehicle recalls. Each of these quality failures had potentially serious safety implications and were not discovered or not communicated to top management for long periods of time.

These and other control failures that will be examined in detail later show that blaming individuals or companies for the problem is not addressing the core issue. Continuous economic losses from poor quality are acknowledged globally and by an overwhelming majority of companies and governments. In fact, the Six Sigma movement (Motorola) and, latterly, Lean Manufacturing are testimony to the acknowledged need to improve the control of all type of industrial and business processes. Neither of these quality methodologies addresses the process control method that is at the heart of most processes, however.

Mike Brisk, of Sydney University in Australia, performed surveys of PID (proportional–integral–derivative) control loops in both the United States and in Australia[3] because of a perceived lack of attention to the basics of process control. He found that between 61 and 65% of the 100,000 PID loops surveyed in each country were not operating correctly (either turned off/manual, or having exceeded their control ranges). His conclusion from these surveys was that we need to pay attention to the controllers and make sure they are operating before considering so called "advanced control" systems. This conclusion clearly has veracity. However, we also must concede that the basic principle of the controllers in these cases has certainly failed; that is, the regulation of the control variable by the controller has failed to allow regulation of the process over the long term. The widespread nature of this failure argues against special causes or "operator error." The real reason must be that it is not addressing the real reasons for the process varying away from its target.

Given the far-reaching consequences of control failures that will be further exemplified in the following chapters, a working hypothesis from the above examples is that **production plants are not intrinsically "in control" or stable.**

Despite modern technologies and automation systems, control failures are endemic in all materials processing and manufacturing industries as indicated in Table 1.1. Even Toyota with its world leading production system has had major control failures in the past few years. Therefore, it is not a question of any production plant losing control of its quality or economic competitiveness. Rather, it is a better assumption that a production plant is not in control in many of its core processes. The job of the production staff then becomes one of **getting control over the critical process variables and practices** that determine the final outputs of the production plant. This is a mission that broadens the purpose of control to include problem identification with data and problem solving. When it is understood that all staff contribute to the new control objective, we are actually redefining the whole of the work of production.

It was 6 a.m. on the smelter road, dark and cold. Rob drove up to the guard at the gate. "Rob Johnston."

The security guard picked up the phone: "A Mr. Rob Johnston, unescorted, Mr. Simcox." A pause.

"Sorry, Mr. Johnston, I didn't have you on my list. Welcome to Southern."

The barrier went up, and he drove down to Operations. The plant was clean and quiet as usual. No one challenged him as he went into the potroom, remembering his mask, stopping at the crew leader's office. "Gidday, Barry. How're things?"

Barry Smith was crew leader for Red shift, in his early 50s, a wiry farmer. He worked at Southern because he wanted to. Never short of a few words,

TABLE 1.1

Typical Control Failures in a Range of Materials Processing, Chemical, and Manufacturing Industries

Type of Production Plant	Market Sector	Typical Control Failures
Materials Handling	Mines: ores, coal	Condition monitoring failures in heavy equipment, associated vehicle failures and accidents due to human machine interface and human behavioral problems.
	Mineral processors: ores, metals	Comminution system failures due to lack of sensing or abnormalities, such as raw material changes, causing loss of control of particle size, dust accumulation, recycle streams, and bag-house pressure drops.
	Logistics: product receiving/delivery (e.g., ports)	Misunderstanding of the purpose of Kan Ban, i.e., Just in Time not Just too Late in terms of availability of parts, components, products. Lean manufacturing, if misunderstood in this way, transfers the delays to the production system and customer rather than reducing cost of inventory and overproduction.
	Packaging plants	Packaging automation system failures caused by lack of detection of changes in setup, substrate packaging material, or sensor performance. Failures in application of packaging chemical coatings or laminates due to lack of sensing of abnormalities in the environment (temperature, humidity), process equipment, or chemicals.
Materials Processing	Food processing: fresh milk, milk products, fermented products	Biochemical reactions in continuous processing can be unpredictable and not observable in real time. Batch operations, such as tank emptying/filling and product delivery, magnify the unpredictability of food quality, freshness, and food safety. Process abnormalities occur, but are only indirectly visible to the current automatic control systems, i.e., as they affect temperature, pressure, or flow currently measured. This requires a quantum step in process analytic technologies and automation.

(*Continued*)

TABLE 1.1 (***Continued***)

Typical Control Failures in a Range of Materials Processing, Chemical, and Manufacturing Industries

Type of Production Plant	Market Sector	Typical Control Failures
	Metal casting, extrusion, rolling plants	Technologies well developed, but abnormalities in solidification, metal deformation rate and temperature, and equipment are not detected or diagnosed except by product QA (quality assurance) or default. This causes embedded process failures and product defects that erode their quality and productivity.
	Chemical reclamation: salt production (NaCl) at Dampier	Heuristic, rule-based control with failures leading to losses of large product "crops." Production processes that rely strongly on environmental conditions, subject to external, structural causes that require feed forward control.
Chemical Transformation	Metal ore refining: alumina refineries, calcium carbide	Corrosive environments lead to accelerated failure outstripping the rate of detection or response. Deterioration of processes and quality is common.
	Refractory materials: silicon carbide, alumino-silicate bricks	Product quality depends on thermal stability during heat treatment, the inputs for which are not controlled.
	Petroleum refining and petrochemicals	Spillage of hydrocarbons from vessels, pipes, flanges is a top event with high potential for subsequent explosion if ignition sources are present. Despite barriers, such as auto shutoff valves, and controls, such as foam sprays and bunded areas, these spillages still occur at a measurable frequency.
	Gas plants and methanol plants	Water and hydrocarbon combined with CO_2 and in many instances H_2S can cause corrosion, hydrate blockages and leaks, or ruptures. High pressures as well as both low and high temperatures, meaning that even controlled releases from the plant can be extremely hazardous. Gas releases can be highly toxic (e.g., H_2S) or carcinogenic (e.g., benzene) or explosive (hydrocarbons) if ignition sources present. Hydrocarbon liquids also present in significant quantities so similar issues as petroleum refining.

TABLE 1.1 (*Continued*)

Typical Control Failures in a Range of Materials Processing, Chemical, and Manufacturing Industries

Type of Production Plant	Market Sector	Typical Control Failures
	Fossil fuel power generation	1. If coal based, plants have a materials-handling issue with subsequent failures in comminution, particle size control, dust generation, lack recycles and bag house problems. 2. If gas fired, then although gas is likely treated, leaks, venting, and ruptures due to corrosion or other reasons can result in explosive risk. 3. If liquid fired, fuel may be heavy and of low quality, e.g., Bunker fuel oil, which results in corrosion failure issues and release can cause fire and explosion risks, with potential for generation of toxic/carcinogenic gases.
	Smelting: aluminum smelting, steel	Poor observability leads to large excursions in individual pots, not categorized as control failures. Perturbations in raw materials or energy supply or equipment failure cause massive loss of "whole of potline" stability, which is in the range $10–30 million per month.
	Plastics: thermoplastics, thermosets, carbon-based composites	Injection and roto-molding quality failures due to inconsistent control of process parameters, such as mold temperature, and due to low understanding of the correct formulation of the polymer inputs. This is exacerbated by a need to produce ever lighter and stronger products from new materials and composites.
Elaborate Manufactures	Automotive	Frequent, short failures in production lines, nondestructive pulling the "Andon" cord. Production companies design and use these failures to allow a help chain of staff to solve problems very fast.
	Electronics boards and assembly	Parts per billion (PPB) quality requirements, but less than one dollar per board. Quality inspection kills margin, but does not prevent failures.
	Specialized construction	Highly variable design and location specific. Quality and cycle time fight each other and depend on the builder on the ground.

(*Continued*)

TABLE 1.1 (*Continued*)

Typical Control Failures in a Range of Materials Processing, Chemical, and Manufacturing Industries

Type of Production Plant	Market Sector	Typical Control Failures
	Furniture	Tradesperson skills with little automation. Rework common (filling and bonding of the composite materials). Control relates to the person.
	Aerospace	Frequent, short failures in production lines, nondestructive. Production companies design and use these failures to allow a help chain of staff to solve problems quickly.
	Marine	Tradesperson skills with little automation. Rework common. Control relates to the person.
	Sawmilling, pulp milling	A combination of solid materials-handling and mechanical operations that is semiautomated with use of steam and chemicals for finishing that is largely automated. Failures associated with human behavioral problems. Steam and chemicals plant hazards include high temperature and toxic chemicals in a highly corrosive environment with risk of ruptures and spills.
	Paper production and high speed films materials manufacture	A combination high speed mechanical processing/manufacturing and also chemical treating/finishing that are both highly automated. Failures due to human machine interface and human behavioral problems.
Finishing Plants	Coating: powder coating, painting, resin-based coatings	Solid and liquid chemicals handling often coupled with high-speed manufacturing. Issues as per packaging plants and paper production.
	Anodizing of aluminum, electroless metal coatings	Solid and liquid chemicals handling. High temperatures. Batch. Semiautomated. Issues as for metal processing.
	Surface treatments: hardening, specialized coatings	Solid and liquid chemicals handling. High temperatures. Batch. Semiautomated. Issues as for metal processing.

Note: Some production processes, such as farming, and oil exploration/drilling, are not considered here.

but it was never more than a few either. “Okay, we’re on schedule so far. I hear you’re here to stay this time.”

“That’s right, Barry. What can you tell me about my new job mate?”

“Well, as long as you sort these carbon problems, Rob … we haven’t been on time more than one out of two shifts these last months.”

He wondered if there was any data on that. “What does ‘on time’ mean in your book, Barry?”

“All the blocks laid out on the line for us. Then we can set them at our own pace.”

“But, you don’t set them all at once, do you, Barry? Why do they all need to be there at the start of shift?”

Barry looked as if a black cat had walked across his path.

“And, the casthouse is no better either … they’re holding up tapping. They have plenty of room in their furnaces.”

“Anything to do with the quality of our pot metal, Barry?”

Another black cat, but no answers. “Well, good luck, Rob. I better get back out there.”

“Yeah, I guess we won’t want to rely on luck too much, Barry. Even a casino doesn’t do that. We’ll talk more about those schedule issues when I get up to speed.”

As usual, a conversation with a production guy set him thinking. What was the effect of schedule compliance on quality of the operations? And the reverse: Did they have measures of either? What were the expectations of the carbon plant and the casthouse about schedule and quality?

“Bet you don’t know where you’re going.” Lee had been production secretary for some years, and Rob was very glad to see her.

“Ah, yeah, that’s a fair comment, Lee. Where am I going?”

At the end of the corridor was his office. The production superintendents, Gary and Ford, were also located there, but both were out in the plant.

“Brian kept things pretty tidy, Rob. See, everything is filed here. Your weeklies, monthlies, the manning, and the financials over here.”

He looked at the neat rows of Figures in the Tables of weekly and monthly data and wondered what sins the averages would take to the grave. ”Are there any charts of this stuff, Lee? I mean over time.”

“No, but I can graph them for you, no problem, Rob; all the data are on the database day-by-day and even pot-by-pot. Brian never asked for that.”

“Let’s wait and see what the right parameters are first, Lee. It might be a big job, so we should start at the right end,” he said, hoping he wasn’t going to be asked what end that was.

“What would be useful is pot-by-pot distributions of the data on the process parameters, though.”

Lee looked at him blankly. Nothing further said. He would need to learn to keep his crazy ideas to himself … for a while at least.

Exercises

1. Explain, with two examples from your own experience, how product quality is connected to process control. In your explanation, use one or more of W. Edward Deming's 14 Points from his book *Out of the Crisis.*[1]
2. How many control failures have there been in nuclear power plants, and what is the most recent example? What do failures in such critical facilities as nuclear plants tell us about the ability of humans to achieve good control?
3. What is the most useful assumption about an industrial process, with regards to the degree of control being achieved?

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2

Tour of the Plant

The DuPont safety manager was due onsite this morning, and Rob was scheduled to meet with him. Orders from HQ, etc. Rob wasn't really sure if he had time to theorize with DuPont guys. What did they know about making aluminum? And, did Southern have a problem with safety? The plant had won a safety award last year.

"He's here to help us improve," said the general manager. "It's also a good chance for you to get some first-hand knowledge while showing him around."

Rob was in his second day at Southern and really needed some time to get to know his team. "Sounds good. I'll see what I can pick up."

Don Russ was waiting at the gate. "Gidday, Don. Rob Johnston. I'm the production manager. Let's get some safety gear for you."

Don was tall and lean. He looked quizzical when I mentioned safety gear but got the point after the safety video.

"Is this your first smelter visit, Don?" He didn't comment except to smile and say, "Pleased to see you. I guess you just started here as well, Rob?"

True. Rob's second day as production manager. However, he had worked here in the past, in R&D. Thinking about it, he knew the plant and its equipment pretty well.

He had never noticed the forklift operating from the back of the Security building before, though, despite having been in there many times. Now, it reversed across their path some 4 to 5 m ahead.

Don had stopped several seconds earlier and now grabbed Rob's arm. "Did you make eye contact, Rob?"

"You have to see *them* first," Rob thought.

"Let's start in the rodding room since that is close, Don. Then we can walk through into the potrooms and, this afternoon, tackle the carbon plant."

Rob was now in full personal safety consciousness mode, watching every direction for the next potentially threatening vehicle.

They had entered the rodding room through the crew leaders' offices by now, and Rob was already making his way toward the anode butts on No. 4 chain. It was always informative to see how the anodes were coming out of the pots, from a process point of view, and that was usually his main reason for being in the rodding room.

Rob noticed that Don was not with him and turned around. Don was still standing by the door just looking at the full range of activities on show. Don's eyes were moving fast around the room as Rob returned to his side. They went quite systematically from the foreground activities where two maintenance technicians were working on the new butt/thimble press to the overhead situation with the power and free conveyers, the conditions on the floor itself, and the activities behind the No. 4 chain where some work was happening around the casting station. What was he looking for?

"Just getting the lay of the land, Rob. I like to do that before entering a production area. Let's go look at what the guys over there are doing." Don was pointing to the maintenance guys at the butt/thimble press.

"Okay, fine, Don. "That hadn't been Rob's first choice for something to look at, but never mind. It was Don's tour. They approached the press, and one of the guys was bent over almost double inside the press looking at a mounting or something. The other guy looked at them as if they shouldn't be there.

"How're you doing, mate?" Don stuck out his hand and greeted the maintenance technician. "You got a hydraulic leak going there?"

Rob hadn't noticed the pool of oil below where the first technician was working on the press.

"Yeah, it's always leaking, this thing. We can't get at the couplings without taking it out for a shift. There's a module changeout that would be better, but we don't use that for some reason." The technician and Don had made a connection, and there was information flowing here, things that Rob had never heard and maybe other production guys hadn't either.

They spent one hour in the rodding room and, by the end, had talked to every person in the area. The crew leader was last because he had been up at the butt cleaner looking at a problem with the cleaning of some butts.

"Gidday, Rob, fancy seeing you down here at the butt cleaner. I thought you were only responsible for making them dirty."

The crew leader was John. Rob knew him, but not that well. "What's the problem, John?"

"Well, the bath is too high, Rob. We can't get the chisel on the butt cleaner to break through to the anode yoke arms. You potroom guys put a lot of material on."

Anode Cover Problems

Fine Anode Cover Material

The effect of poor control of the anode cover, which must be positioned accurately on the new anode from the PTM (pot tending machine) or floor-based vehicle, is a serious issue in probably 50% of all aluminum smelters. It results in bath level variability due to the uncontrolled amount of material added to the pot. The effect of poor cover control on the anode is even more dramatic because the basic function of the anode cover is to exclude oxygen from accessing the red-hot carbon. Airburn is primarily caused by lack of control of anode cover, because the temperature of the anodes in today's potlines rapidly exceeds 600°C (24 hours after anode setting, in fact). Carbon reactivity, therefore, plays a smaller role in anode airburn than in anode dusting, because it is really the supply of oxygen that controls the airburn rate.

Figure 2.1 shows the effect of overflow of an anode cover on anodes in an end-to-end 150 kA pot technology. The cover has partially collapsed in the side channel, and the anode yoke is completely engulfed. This causes the anode temperature to increase to above 900°C everywhere. Carboxy reactivity ($CO_2 + C \leftrightarrows 2CO$) is highly favored thermodynamically under these conditions. Figure 2.2 shows the result of overflowing cover on the anode butt removed from a 340 kA pot in a modern smelter.

The main cause of this problem is the high percentage of very fine, –200 micron cover material (a fraction of this material above 60 wt% will give rise to "floodable powder" behavior in the bulk cover material), which makes it impossible for a PTM or vehicle to apply without overflowing of the cover onto smaller anodes, giving cover levels that immerse the anode stubs and yokes of most anodes well before they are due to be removed from the pot.

Autogenous mills produce up to 80% of this –200 µm crushed bath fraction, and the material is often finer than the alumina blended with it later in the anode cover. However, hammer mill circuits with very high recycle rates also are prone to high dust generation. The specification of coarser product screens (20 mm is much better than 5 mm, for example)

FIGURE 2.1 (See color insert.)
Anode cover material overflowing the anode yokes and collapsing due to its high internal temperature exceeding the phase change temperature of the crust.

FIGURE 2.2
Anode cover on spent anodes in the cooling section of the rodding room. The cover again has overflowed and partly buried the anode yoke, creating high temperature and melting beneath it.

that do not blind as easily (release angle, aperture geometry) can relieve the recycle rate in this type of circuit.

Unfortunately, it is the case that the downstream materials handling systems actually require fine crushed bath material production because of the use of vertical airlifts from pressurized tankers, or long runs of dense phase conveying. These systems require –3 mm of crushed bath product, generally, or blockages can occur. These conveyers are considered cheaper to install but consign the potroom operations staff to dust-filled rooms and uncontrollable pot materials and energy balances. Bucket elevators and other belt conveying systems (e.g., folding belt sicon conveyers) can easily replace them and achieve a quantum reduction in the –200 μm dust fraction that pollutes both the pots and the potrooms where it settles on all horizontal surfaces, recycling many times before leaving through the potroom roof or basement.

The process safety implications of high dust loadings have now been studied by a number of smelting companies with specialized university support,[1] demonstrating that the bath processing circuits are often implicated because of the above design issues. This is related directly to a lack of customer requirement definition and quantification of the economic and environmental consequences of not meeting these requirements in a given smelter. For example, the cost of a fine anode cover has been quantified practically and is an extra 0.02 kg carbon anode[2] required per kg of aluminum production in most smelters, but these data are seldom used to justify the modification of bath process circuits. Operationally, generation of dust in smelters is a severe exemplar of lack of control and is a leading indicator of both process and safety performance deterioration.

ALUMINA FEEDING SYSTEM RESULTING IN OVERFLOW OF ALUMINA ONTO ANODES

Figure 2.3 shows the large quantities of alumina that can quickly build up on the anodes and the feeding channel of pots if the feeding system develops problems in delivering the alumina to the bath. Figure 2.3a shows a breaker that is not able to penetrate the crust and thick alumina built up on top of it. Alumina builds up and is occasionally raked away by operators.

The anode yoke is eventually engulfed by this alumina and must be "stored" on the anodes or raked out of the pot altogether if possible. Figure 2.3b and Figure 2.3c show the result of this situation, which is a massive material and energy imbalance at the top of the pot that is later transferred to the cathode when excess alumina on the anodes and feeding channels is deposited onto the cathode as sludge (usually when opening blocked feeder holes or changing anodes, or through collapse of the crust).

Both of these situations result in excessive levels of cover on the anode and over the steel anode yoke, although the profiles and composition of this overflowing material are different in each case. As shown, the first mechanism of *anode cover overflow* tends to be heavier on the side channel end of the anodes and is responsible for side channel crust collapse and anode airburn in this location. The second overflow mechanism comes directly from the feeders and is alumina. This is heavier on the center channel end of the anode and causes center channel collapse, massive alumina sludge formation on the cathode, and center channel anode airburn.

This second overflow mechanism is more serious for another reason, the formation of the corundum (extremely hard aluminum oxide) phase in the mainly alumina material high on the anode yokes.

Corundum formation in the midsection of a crust cross section is shown in Figure 2.4, where the phase analysis will show equal proportions of alpha alumina and chiolite phases intimately mixed in "core and shell" aggregates that are very hard and also resistant to fracture.[3]

This material, therefore, is extremely difficult to clean off the anode butts in the rodding room and causes manual intervention on the cleaning machines, which can be a serious safety issue because of its frequency. The corundum phase forms a tough interlocking structure with chiolite (condensed bath fume) in the upper parts of the crust, and this gives it fracture toughness against crushing by the bath processing system as well at many smelters, particularly those that rely on drop-shatter crushing, such as autogenous grinding mills and gravity discharge mills (rotary breakers).

Driver mechanisms for this "excess alumina" problem are poor feeder performance (delivery of alumina into the bath); mechanical problems, such as crust breaker cylinder weakness; overheating of the

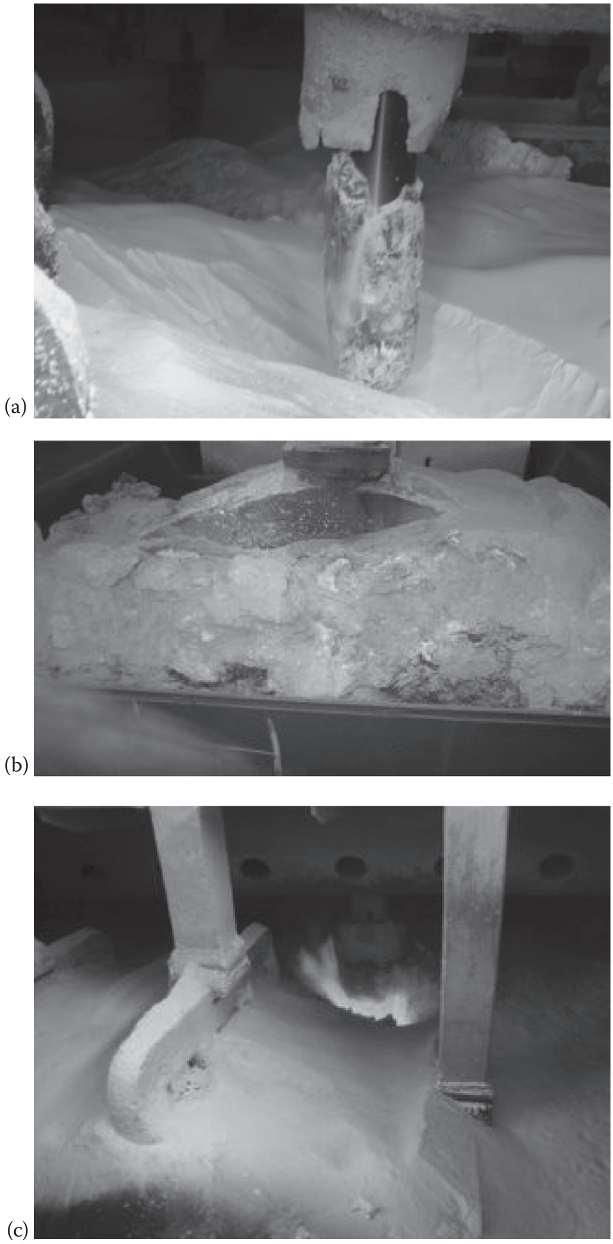
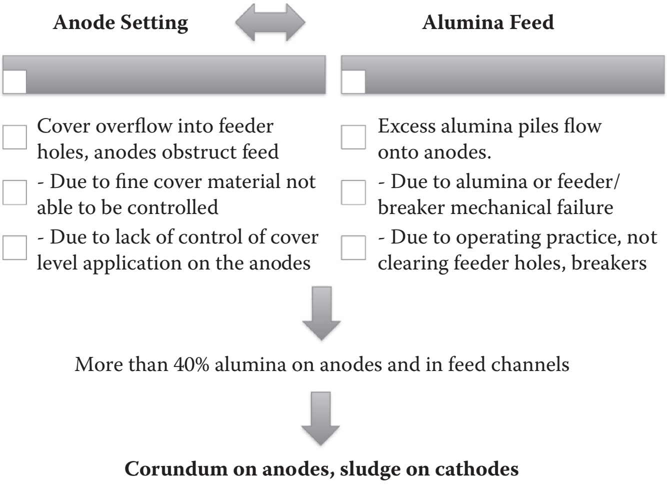


FIGURE 2.3 (See color insert.)
a-c. Three photographs of high amperage pots in which the alumina is being fed partially onto the cover and anodes, rather than into the bath, through problems in the alumina feeding systems.

FIGURE 2.4
In this case, the alumina from the feeding system has built up right to the level of the aluminum/steel transition joint with the anode rod, causing a serious risk of failure of the joint or weld due to temperatures above 350°C.

breakers themselves until bath buildup on them (shown in Figure 2.4) prevents alumina addition to the feeder holes; poor control of the feeder hole geometry due to operational practices; and plugging of the hole. Ironically, the plugging of feeder holes also is caused by very fine anode cover (problem 1), which overflows into the feeder holes at anode setting, or by imprecision of anode replacement (i.e., anodes kicked into the center channel) or too much anode cover material placed in the center channel.

This is a good example of the complexity and interdependencies between the cover materials and the operations in smelting cells and is summarized below.



Anode Setting ⟷ **Alumina Feed**

☐ Cover overflow into feeder holes, anodes obstruct feed
☐ - Due to fine cover material not able to be controlled
☐ - Due to lack of control of cover level application on the anodes

☐ Excess alumina piles flow onto anodes.
☐ - Due to alumina or feeder/breaker mechanical failure
☐ - Due to operating practice, not clearing feeder holes, breakers

More than 40% alumina on anodes and in feed channels

Corundum on anodes, sludge on cathodes

It also is important to note that not only point feeding pots are subject to the above problems, and that both Problems 1 and occur on technologies with center break/dump and side-feeding mechanisms.

Rob looked at the material around the yoke arms. He grabbed a 5 kg piece of the crust that had fallen off and dropped it from a height onto the concrete. After four attempts at this, the piece developed visible cracks inside, but still it didn't break in two. It was corundum all right; basically, alumina sintered and heat treated with bath fume. Why were the potroom operators using alumina on top of the anodes? Why so much material?

His thought process was interrupted by Don who had seen something.

"What is that guy doing, John?" Don said to the crew leader, pointing to the operator who at that moment was inside the butt cleaner guarded area with a crow bar trying to lever the hydraulic chisel out of where it was jammed in the bath between the anode yoke arms of a butt.

"Is that machine isolated?" Don said, speaking to the crew leader, up close so he couldn't be misunderstood.

"If we did that, we'd never clean any butts, Don." John shook his head.

This was Rob's patch. "Never mind production, John. Let's shut the machine down properly and get it cleaned up so we can analyze the problem. I want some pictures of this situation just as it is now as well."

They left John and started walking toward the potrooms. "Which line would you like to look at first, Don?" Rob was looking forward to having a good look at the pots.

"Actually, can we go to your office now, Rob? I think we might have a little work to do." Don was already walking to the offices.

Don asked for some paper. "I'd like to go through what we saw out there in the rodding room. Give me your list first."

Rob had written down five things: the butt press, the nonisolation of the butt cleaner, the airburn on the cleaned butts, the high anode cover on the uncleaned butts, and the cast iron that looked to be cracking in the new anodes before they got to the potroom.

"That's all useful, Rob. I'm sure you will follow up those observations from a production point of view. But, do you think there might be some things you missed? I mean things about safety?"

Don was sketching up a table, a big table. He hadn't taken any notes out there. However, there was plenty he had seen, and plenty Rob hadn't.

Rob thought about the important things he had seen—about the process. But, the flip side was that if someone was hurt because he had walked past an unsafe act or condition, all those important process observations and ideas in his head wouldn't mean much.

The Observations of a Safety Professional in a Production Environment

The list in Table 2.1 focuses on examples of the highest injury/fatality risk categories as experienced in mining and smelting operations within one company in the period 1995 to 2000. The observations in Table 2.2, made during the same audit, place the emphasis on the underlying behaviors of people in the area and in management.

In all, there were 26 key safety observations made during the short visit to the rodding room of the smelter.

When the table was finished, Don was quiet and so was Rob. How had he missed so many things that Don had not? It was Don's first time in that factory, and his first time in any smelter as far as Rob knew.

"What you observe when you go into a factory, or any place where people are working, is not a matter of what you might be interested in, Rob.

TABLE 2.1

Specific Safety Observations Made in the Rodding Room During a Short Visit (11 Observations)

Risk Category	***Observation***	***Potential***
Body position	Maintainer bending double for prolonged period, due to poor maint. procedure	Back injury
	Using your back as a crane to lift out hydraulics couplings	Permanent injury
	Levering a hydraulically actuated chisel jammed in the bath on an anode butt, using a crow bar.	Shoulder or back injury
Isolation of machinery	Operator inside the butt cleaner and working on a hydraulically actuated chisel jammed in the crust on a butt.	Fatality
	Manual actuation of the butt cleaner controls when people were inside the cleaning machine isolation zone	Fatality
Explosion risk/molten materials	Casting into wet stub holes, or with wet graphite solution on the stubs – eruptions of molten metal out of the stub holes observed. No exclusion zone around the anodes or casting ladle.	First degree burns
	Aluminum powder/dust allowed to build-up on horizontal surfaces on spray station furnace with molten metal inside (recent fire on top of furnace). Dust explosion risk?	Multiple fatalities?
Working at height	Maintainer on top of spray station inspecting smoking material, had no fall restraint and 2m in the air.	Fatality
Vehicles	Forklift reversing and unseen until too late – no audible or visual alarm and no eye contact with pedestrians.	Fatality
Suspended loads	Operators walking under anode rods on the Power and Free	Fatality
	Operator man-handling the suspended casting ladle to the anode pouring station	First degree burns

TABLE 2.2

Follow-up Observations about the Safety Systems from the Same Rodding Room Visit, Made in the Hour After the Visit (15 Follow-up Observations and Questions)

Risk Category	*Observation*
Attention of frontline supervision	Maintenance Crew Leader not present or aware of the risk of back injury on the butt press during maintenance job.
	Modular change-out procedure for butt press hydraulics not implemented? Production first and Maintenance staff not consulted.
Interdependence of staff	Maintenance staff not intervening with their colleagues before or during an unsafe act (eg. body position).
	Operators not greeting and challenging strangers.
Operational risk assessment processes	No 'Take five' or other formal risk assessment for maintenance tasks on butt press or spray station maintenance operations.
	Hazard studies for anode casting, butt cleaning processes not done or not available (both facilities constructed in last two years)
Engineering oversight and analysis on safety of structures/processes	Engineering analysis/input into the maintenance processes for the rodding room not evident. butt press, butt cleaner forces and capability for automatically processing butts – not capable.
	Capability of the hydraulic systems on butt press, butt cleaner not assessed in the face of high frequency of breakdowns/jams.
	Process safety implications of molten materials documented in the company Molten Materials Audit 12 months ago. Actions of Management since this Audit?
Safety rule communication and commitment by management/staff	Forklift driving behavior – not challenged by Crew Leader or Superintendent?
	Not wearing or insisting on respiratory protection when in dusty areas such as butt cleaning or butt transport.
	Safety rules not posted in the factory, not known by the Operators or Maintenance staff.
Safety interaction processes (e.g. STOP)	Operators walking under anode rods on the Power and Free. Seen by other people many times but no intervention or discussion.
	Operator interfering with a suspended load (casting ladle) under the gaze of the operator in the casting cabin. No discussion about the risk or the reason for this action.
Management safety system	Not working on any of the above safety issues (and people aren't involved in safety improvement). Is there a Site Safety Committee to assign tasks re the above issues? Are there individual committees or teams to address and control the improvement of them? What is the structure of the organization in respect of safety? How are the Experts (the Staff) involved?

It can't be about production. It's about ensuring that no one gets hurt. What we say at DuPont is that if you can't manage safety, you can't manage anything."

Over the following days, as he thought about it more, Rob began to see what Don had done. There were only 12 people working in that factory during the tour, and Don had observed and talked with every one of them. They were the ones whose personal safety was at stake. In those discussions, some deeper issues had begun to emerge, and they were listed in the second part of the table that lay sketched out in front of him.

This part of the table painted a picture of lack of control—control of the equipment that was malfunctioning frequently and of process materials certainly, but, behind that, a lack of control of the work of the staff who were responding or "reacting" to these problems. Most of all, there was a lack of control by the leaders. Were there written safety rules for the plant? If so, why were they not applied? Were the fatality risks recognized by management? Were actions underway to eliminate these risks? There was nothing about this in the neat files and tables of financial and production data in Rob's new office.

Driving home along the straight smelter road much later that night, Rob thought about what he now knew concerning the risks and possible consequences of production. Was it possible to control these risks? If Rob couldn't control them, what chance did he have of controlling the aluminum purity or the energy consumption?

The mobile phone rang later that night. For some reason, the sound woke Rob instantly. Waking up sweating with phone in hand was a new experience.

Exercises

1. What is the most common control failure outcome in the preparation of crushed bath cover for anodes? Give two mechanisms by which this occurs.
2. In Table 2.1, what is the common factor in most of the safety observations given? Are there any unsafe conditions identified in the table? How have these conditions originated in the plant?
3. What is the effect of variation in the level of anode cover on anode butts returned to the rodding room? How can this result in unsafe acts there?

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3

Welcome to Production

The visit of the DuPont guy had been an energizing experience for Rob, in spite of and because of the hard lessons. No one got hurt and nothing was damaged or destroyed when there was plenty of potential for both.

Rob had been around a while, long enough to know that in production you needed to be pragmatic. Not everything could be predicted ahead of time, and maybe not everything could be prevented right now. However, you work to get better. If you don't, you get worse.

Thus, Rob's agenda now was to get ahead of the game. Find out what was going on in the carbon plant where he hadn't yet set foot as production manager. Of course, he thought he knew what went on there; however, that also had been the case in the rodding room.

"What's happening, Shaun? Last time I saw you was in potline 2."

"That was years ago, Rob. I'm a carbon guy now. I don't know what those potties are doing with our beautiful anodes," remarked Shaun, who had a dry wit that had served him well during his up and down years of potline operation.

"Well, since you are such an expert, how about you show me how you do it?"

Rob started in green carbon with the liquid pitch system. This was composed of two 5,000-ton, liquid pitch storage tanks, and the facilities to heat (using heat transfer fluid (HTF) and electricity) and pump the pitch around a recirculating loop before adding it to the batch mixers. The HTF system uses electrical heating and a series of heat exchange circuits and pumps to maintain the temperature of the pitch storage tanks, aggregate preheaters, batch mixers, and pitch piping.

On that day, there were virtually no people in the area—only one maintainer who was doing a routine Preventive Maintenance (PM) on the HTF header tank and heating system. Not an operator in sight. Rob waved to the maintainer who was inside the bund wall of the tank and introduced himself.

"I never saw the last manager, so this is a special day," said Grant, who was a burly, experienced fitter with a gas fitting ticket.

"Is it usually this quiet round here, Grant?" Rob knew there were two-person shift maintenance teams working across the entire carbon plant, and Grant was one of the two on this day's shift.

"Well, it's completely automated, Rob. We don't need any operators except to monitor and look for leaks. And, maintenance has been virtually the same since we improved the tank's vent pipe design so it vents directly into the bund. Before that, it used to spout condensate all over the plant when an over-pressure happened. Now, we don't have a single drop to clean up.

Rob and Shaun walked round the corner of the building into the vibroformer area and started up the stairs to look at the mixers. Something was puzzling Rob about the last conversation, but he couldn't put it into words.

A deafening thunderclap. Then the sickening sound of metal rent asunder and masonry crushed.

Both men lost their footing. Handrails saved them. Rob felt nausea rush up from his stomach into his throat. He steadied himself against the rail and took some deep breaths.

Running around the side of the building, Rob saw the end of the HTF header tank embedded in the blister block wall, and Grant sat on his backside a few meters away, puking, sheltered from the blast by the wall. He must have come out of the bunded area around the header tank seconds before the blast.

Meanwhile the tank itself had caught fire and was burning with a jetting, luminescent flame as the cracked, light hydrocarbons burned off. The siren came about three minutes ahead of the fire brigade, and with a light-headed feeling, Rob saw that the process of disaster control was in full swing.

HTF Fires in Aluminum Smelters

Both fires and explosions are documented occurrences in the green carbon plants at smelters. Even before the advent of liquid pitch, which replaced solid pencil pitch in the late 1980s, the heating of the crushed, dry aggregate, pitch melting, and mixing equipment in the green carbon plant required a heat transfer fluid (HTF) system. The HTF is a heat transfer oil with a typically wide operating temperature range and high flash point, as shown in the typical oil specification in Table 3.1.

TABLE 3.1
Typical HTF oil Specification for a Green Carbon Plant

Composition	Alkyl substituted aromatic
Appearance	Light yellow liquid
Density	971 kg/cu.m
Kinematic viscosity (40 C, DIN 51562 Part 1)	4.0 mm^2/s (cSt)
Temp for Kinematic Viscosity of 300 cSt	−39°C
Pour Point (DIN ISO 3016)	−61°C
Flash Point, COC (DIN ISO 2592)	146–155°C
Fire Point, COC (DIN ISO 2592)	154–165°C
Boiling Range:	10% 296°C
	90% 319°C
Maximum Operating Temperature (prolonged)	275°C

However, these oils do not remain stable over long periods at the quoted operating temperatures or even below. Over a period of months and years, they are thermally decomposed to "lights" from cracking and also to a residue of larger molecules or carbon particles from fouling/coking on the heat transfer surfaces. The "lights" give rise to a higher vapor pressure and a lowering of the flash point over time, with a greater risk of ignition in the vapor space above the HTF in the header tank. This elevated risk of ignition as a function of flash point is well known because of the experience in the petrochemical industry.

Real fires that have occurred in HTF installations are exemplified in Figure 3.1; the first fire was isolated to the HTF header tank itself, while the second fire that also originated in the header tank damaged the green carbon plant in the secondary fire that resulted.

HTF process safety risk is extreme because of the initial explosion in these incidents and the subsequent fire damage that can create greater

FIGURE 3.1
HTF (heat transfer fluid) fires at smelters that have caused significant damage and downtime as well as potential fatalities. (Thanks to Barry Sadler for his observations on a number of carbon plant fires and investigation discoveries.)

FIGURE 3.1 (***Continued***)

potential for fatality if the fire spreads to the green carbon building itself. This building is usually multistoried and can contain 2 to 20 personnel, including control room staff. In these respects, a fire in the liquid pitch circuit is equally as destructive as one in the HTF system itself.

Rob walked into the general manager's office the next morning. He had talked with John the night before about Grant's condition. He could easily have been killed—but wasn't. That was the good news.

"What's the condition of the plant now, Rob?" John Simcox came straight to the point.

"We've lost the HTF circuit, John. We're using the electrical trace heating to keep the pitch from solidifying in the pipe, and the storage tanks are okay. The guys are working to restore the HTF header tank and the piping damaged in the fire. Luckily, green carbon is undamaged. However, without HTF, the plant will be down for the rest of the week." Rob had been at the plant until 10:30 p.m. the previous evening.

John's hands were tensed, and Rob thought he saw a tremor. "This was a potential fatality or even a multiple fatality, Rob. I want you to investigate this one personally. Put everything else on hold. You can have anyone you need for the investigation team. That's it. I want an update every day, starting at 5 p.m. this afternoon."

Rob already had his superintendents from the previous evening getting all the information together from the carbon plant. Their first response had been contingency plans and continued production, but Rob had directed their work back to the accident itself and shut the plant down. Two questions were now asked but not answered:

1. The HTF target temperature had been raised repeatedly over a six-month period, but the target dry aggregate and pitch temperatures were not being met consistently. What was the risk with raising the HTF working temperature? Was the alarm raised?
2. The last recorded flash point tests on the HTF showed a reduced HTF flash point (well below the spec of 145°C). This would have led to increased ignition risk in the HTF header tank vapor space due to breakdown of the oil into more volatile "lights". Was there a point when this risk became unacceptable, at which time the oil should have been changed, and what was this trigger point?

However, there was something else. Something that the maintainer, Grant, had said that was still worrying Rob. He decided to bring in an expert to look at the design of the HTF system itself.

"Who can help us understand this system, Shaun? I'm not impressed with the standard of documentation we have about it here. It's incomplete and all seems to date from the time of installation. There have been no updates since then."

"Yeah, that's true, Rob," Shaun said. "The suppliers gave us this stuff, but they said it is basically a 'set and forget' system. No big changes needed. Just keep the temperatures in range."

There was silence. Rob looked at Shaun. Breathtaking … set and forget. Rob couldn't quite believe what he was hearing. But, this hadn't been Shaun's control philosophy, just what he had been left with by the suppliers. How could Rob get behind the lack of analysis here?

"Who else can I can talk to about this type of system, Shaun? Who really knows?"

"Well, the best person on these systems is not only an aluminum guy, Rob. He doesn't come to the plant now. The previous manager didn't need him. But, I think he was the real expert. Barry James is his name. He's worked in the petrochemical industry as well as aluminum, and we all thought he was the best all-round consultant on carbon. Still lives nearby. I can find his contact."

"Get it for me, Shaun."

Barry was here by the following day. At 4 p.m. the team was standing around the carbon plant conference room table on which the HTF system working drawings were spread out. Barry was explaining the rationale for the plant operation, including the HTF circuit and its limitations.

"You see the heat exchange efficiency is the key thing in HTF systems," Barry said. "That means the temperature difference between the HTF itself and either the pitch, the dry aggregate, or the paste, compared with the heat flowing between them."

On the whiteboard Barry was doing heat transfer 101 for them:

$$Q = U\ A\ \Delta T_{LMTD}$$

where

Q = Heat duty to achieve target temperatures, either to the dry aggregate, pitch, or the paste, kW.

A = Heat exchange surface area, which can become fouled by burned pitch, paste, or deposits from HTF, thereby increasing its resistance to heat transfer significantly.

U = The overall heat transfer coefficient, which includes any ‘fouled’ surfaces.

ΔT_{LMTD} = Log mean temperature difference between the HTF and either the aggregate, paste, or pitch. If U decreases over time, this temperature difference must increase in order to transfer Q, in order to meet the target temperatures.

Now Barry was leaning over the drawings and pointing. “If the heat transfer efficiency reduces on any of these heat transfer surfaces, either here on the HTF heaters, here in the aggregate preheaters, on the pitch pipe jackets, in the pitch heat exchangers, or in the jacketed mixer shells here, then the same temperature difference will not transfer the required heat duty, and there will be a requirement for a higher HTF temperature to transport the heat. But, this is not really the way the control system works locally. It is a series of HTF flow control loops fed by the main HTF pumping loop.”

Rob looked at the schematic of the HTF process flow diagram before them (Figure 3.2) and questioned, “So the first control mechanism for meeting the dry aggregate temperature or any of the other temperature targets is to increase the HTF flow rate?”

“Yes, that’s it, Rob. The higher flow gives a higher local HTF temperature if there is already a big temperature drop through the HTF system. But, then, there is a manual control loop outside this, once that flow control has maxed out. This is the diagram here (Figure 3.3); see the link between the dry aggregate temperature and the local HTF temperature? That gives you the ability to manually increase heat to the HTF heating circuit through its controller in the main diagram. Thus, HTF set point temperature can be increased, as was done a number of times in the past year. Unfortunately, high HTF set point temperature creates a risk of fast cracking of the oil—within minutes, in fact. And, that means a really high risk of explosion and fire in the HTF system.

“The problem really is that the control loops assume that the need for more heat transfer can be met by increasing the HTF flow to each heating application, but that is often not addressing the longer term problem, which is deteriorating heat transfer across the surfaces due to fouling, corrosion, vapor production, or breakdown of the oil, or pitch solids buildup on the pipes and other surfaces. Eventually, all of these things have to be fixed, or there have to be higher local temperatures and higher main HTF temperature over time.”

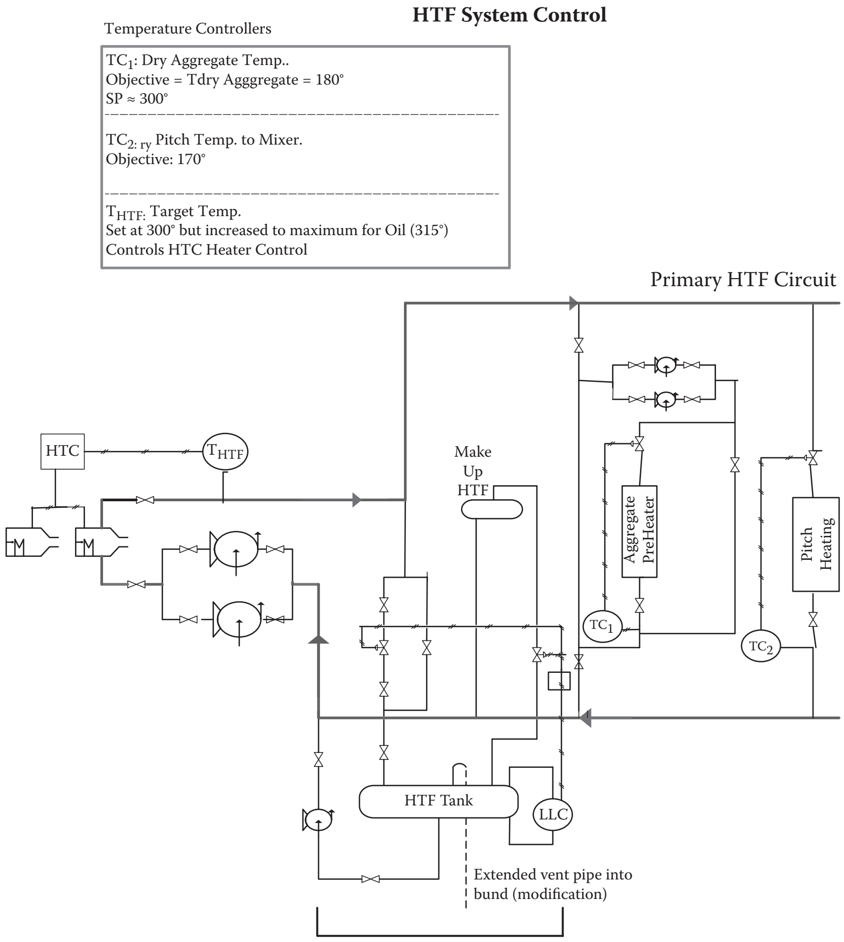


FIGURE 3.2 (See color insert.)
Main schematic of the HTF system.

Everyone was listening. Rob could see that this was the first time they had heard this information.

"Barry, can I see you later?"

Rob was frustrated by what seemed like very simple issues of control. Where was the design HAZOP (hazard and operability) study on this control system? Why didn't the automatic control system address the real causes of the variation: heat transfer efficiency? Why was there no connection with the control of the HTF system and its equipment operation or maintenance?

"I can see how the drop in flash point and the manual increases in HTF temperature set point will increase the risk of explosion or fire, Barry," said Rob. "Those are key findings for us. But, it doesn't tell us when to respond, or?

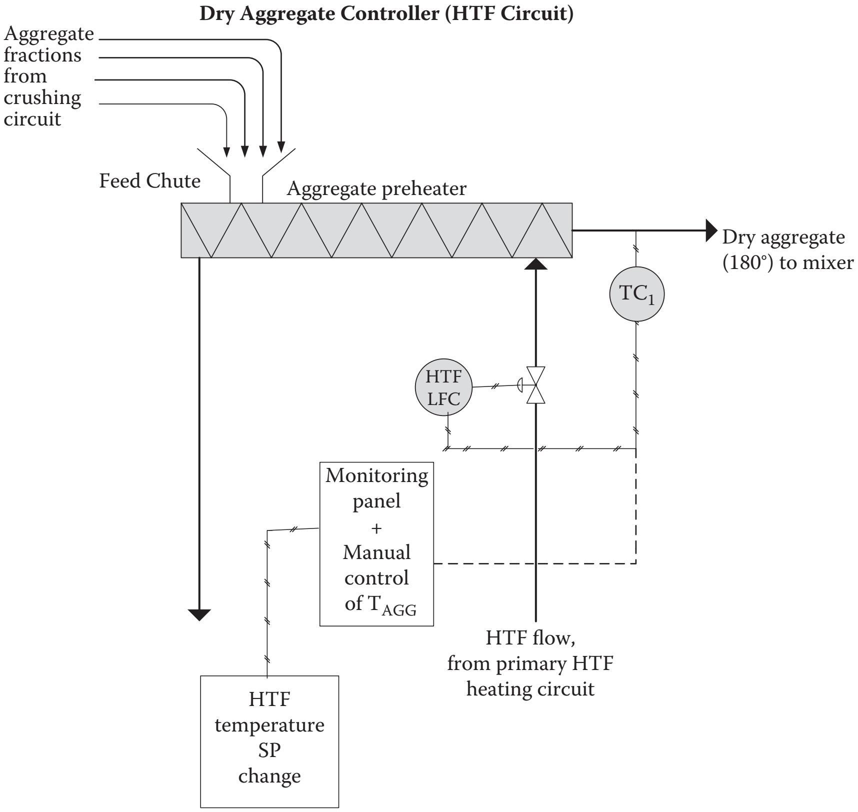


FIGURE 3.3
Schematic of the dry aggregate part of the HTF circuit.

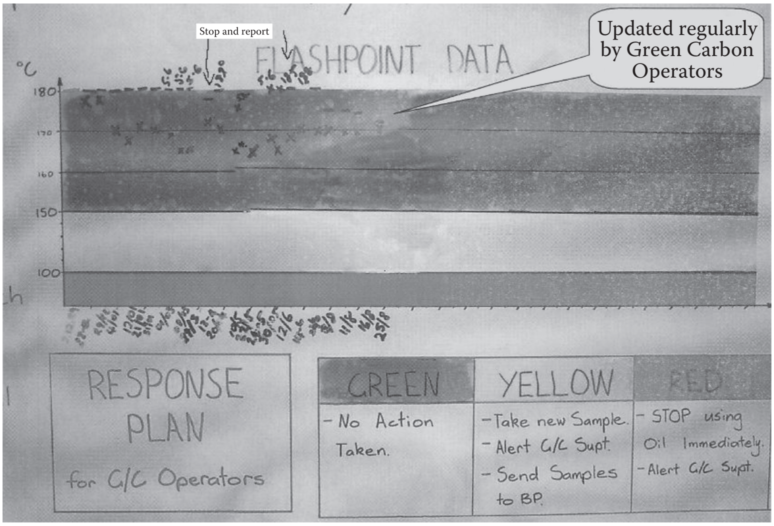
what are the triggers for increases in the HTF main set point temperature and the drop in flash point."

"Well, that's a matter for you, Rob. There are at least two reports I wrote three years ago specifying those trigger points. It's not a secret. But, someone at the plant here has to pick it up and make it part of your control for HTF. I mean the real actions are going to be by your operators and then by maintenance guys who take the system down to clean it or replace the oil."

Control of the Flashpoint of HTF

The HTF flash point can be monitored routinely each week, as shown in Figure 3.4.

The trend in HTF flash point is generally downward, but with significant point-to-point variation. A "precontrol chart" of the weekly measured flash point is very useful in making the decision to investigate HTF deterioration.



GREEN	YELLOW	RED
- No Action Taken.	- Take new Sample. - Alert G/C Supt. - Send Samples to BP.	- STOP using Oil Immediately. - Alert G/C Supt.

FIGURE 3.4 (See color insert.)
The precontrol chart of HTF flash point data, with the response plan for operators of the green carbon plant below the chart. (Courtesy of New Zealand Aluminium Smelters, Tiwai Point, New Zealand.)

When a downward trend occurs over several months and the data fall consistently in the "Yellow" zone, this indicates that there is a need to investigate but not an appreciable risk of ignition of the vapor space. This is the time to plan the next HTF system maintenance period. This type of chart becomes the focal point for scientific decision making by operators in production, encompassing both the measurement system and its sources of error, along with the trend in the data and its statistical variation, and, of course, the trigger for action (Yellow or Red). The fact that the response plan for when an action is required is also on the chart makes ignoring the signal almost impossible, because you can see at a glance what needs to be done. A measurement in the Red zone gives the operator the discretion to stop production, the equivalent of the Andover cord in the Toyota Production System (TPS). This system has been developed by operators and is assessed to be best practice in the industry.

Rob took a deep breath, and counted to 10. However, that only seemed to increase the pressure inside him. Why was there no evidence of a management process here? The frequency of cleaning of internal equipment surfaces and replacing the oil wasn't even specified in the PM schedule.

"Okay, I also want to know if there is anything that might be a direct trigger here, Barry? I mean what was the immediate cause of this particular explosion?"

Barry was noncommittal. "Sometimes they just happen, Rob. There might not be a smoking gun. It could have been a spark or a drift of hydrocarbon vapors to an engine or motor, or a switch failing and arcing."

Rob walked back through the plant to calm down. This was not the first time he had lost himself in the activity of production, and gradually the feeling of impotence dissipated. He turned down through the anode storage area where he hadn't walked for a while. Just the act of walking somewhere new was helpful.

"Hey, do you have the crew leader's authorization to be here?"

Rob turned and saw an operator, or at least the teeth of an operator, because the rest of him was jet black. He was coming out of the bake and had seen Rob walking through the anode storage area.

"I'm the new production manager, Rob Johnston. How are you doing?" Rob didn't know the operator.

You're Rob Johnston? Okay, then it's good to meet you. I'm Jim. But what are you doing here, Rob? We have overhead cranes here, and duct cleaning work, plus flue wall construction and transfers. We like to know who is in the area."

"Yeah, good point, Jim. I'm still on a learning curve here. I've been with the crew leader, but I should've told him where I was headed. I guess you know we had an accident over in the green plant. I'm leading the investigation."

"Yeah, that was the HTF system, wasn't it? That thing has never really been operated properly since we got it. We been saying we needed new oil for about six months—the flash point says we do. But, no new oil. And the maintenance guys keep changing the system. Like the venting pipe brought down lower into the bund wall area; who said that was a good idea? Anyway, what do I know? I'm just an operator. See you later, Rob."

Jim was gone with a flash of teeth and not much more. However, he had said the thing Rob had needed to hear. The vent pipe. An improvement … or what?

The next day, first thing, Rob said to Barry, "So, Barry, what is this vent pipe here? Where was it originally?"

Barry's head was now about six inches from the drawing.

"S@#t! When was that changed? That's the breather pipe for the HTF tank. If you stop the 'lights' from coming out of the tank, they have nowhere to go. In this configuration, the hydrocarbons lighter than air won't be able to push the air out of the pipe. That means the vapor pressure of lights will go up in the tank and, potentially, reach the explosion limit, whatever the flash point of the oil is. In fact, there could be an explosive mixture of HTF and air in the vent pipe itself leading to an explosion there."

Rob sensed he was getting close to the immediate cause of the accident. He called the engineering manager.

"No, we didn't get consulted on any modifications like that, Rob," he said. "Actually, I was looking at our 'as constructed' drawings just today. They don't show a change to the vent pipe."

Next came the maintenance superintendent.

"Yeah, we made that change a year back," he said. "It's really reduced our work in cleanup around the HTF tank area. We told the operations we were doing it. We didn't get any objections."

Once again the slow count to 10 in Rob's head. He found it wasn't as bad this time. Was that a good thing? Rob didn't think so. It was like finding that the tip of an iceberg was really connected to something much bigger.

Pathogens or Latent Conditions, and the Swiss Cheese Model (James Reason)

The traditional formulations of a compensatory control system do appear to extend across the whole of the plant. These control systems respond with arbitrary changes in a manipulated variable whatever the cause of the variation is (or isn't). In the language used by James Reason (referenced more closely below), these systems introduce a "resident pathogen" into every industrial control system because the real cause of the variation, whether it be anticipated in the original design or not, remains hidden as a latent condition, waiting to reappear when the system enters this state again. James Reason drew the following analogy:

> At Chernobyl, for example, the operators wrongly violated plant procedures and switched off successive safety systems, thus creating the immediate trigger for the catastrophic explosion in the core. Followers of the person approach often look no further for the causes of an adverse event once they have identified these proximal unsafe acts. But, as discussed below, virtually all such acts have a causal history that extends back in time and up through the levels of the system.
>
> Latent conditions are the inevitable "resident pathogens" within the system. They arise from decisions made by designers, builders, procedure writers, and top-level management. Such decisions may be mistaken, but they need not be. All such strategic decisions have the potential for introducing pathogens into the system. Latent conditions have two kinds of adverse effect: they can translate into error-provoking conditions within the local workplace (for example, time pressure, understaffing, inadequate equipment, fatigue, and inexperience) and they can create long-lasting holes or weaknesses in the defenses (untrustworthy alarms and indicators, unworkable procedures, design and construction deficiencies, etc). Latent conditions—as the term suggests—may lie dormant within the system for many years before they combine with active failures and local triggers to create an accident opportunity. Unlike active failures, whose specific forms are often hard to foresee, latent conditions can be identified and remedied before an adverse event occurs. Understanding this leads to proactive rather than reactive risk management. To use another analogy: active failures are like mosquitoes. They can be swatted one by one, but they still keep coming. The best

remedies are to create more effective defenses and to drain the swamps in which they breed. The swamps, in this case, are the ever-present latent conditions.

James Reason[1]

The implicit but unstated assumption in the traditional control design examined here is that the cause of variation is known and, therefore, that a control variable can always be manipulated to reduce/remove deviations from the target. In this control design, if there are other unknown causes of variation, they will not be removed. These causes are referred to above as pathogens or latent conditions. They are being continuously embedded in the system, as shown in another of Reason's famous analogies, the Swiss cheese model (Figure 3.5):

In this analogy, the multiple protection layers put in place in a modern industrial plant are envisaged as many slices of cheese. These protection layers are designed to provide safeguards such that incidents or initiating causes do not lead to a loss event.[2] These multiple safety layers are also known as defenses in depth in Reason's "Swiss cheese" model.[3–5] The analogy further considers holes in the different slices of cheese as representing active failures and latent conditions, or missing barriers and latent weaknesses. The solid parts representing barriers and various operational safety measures prevent penetration or

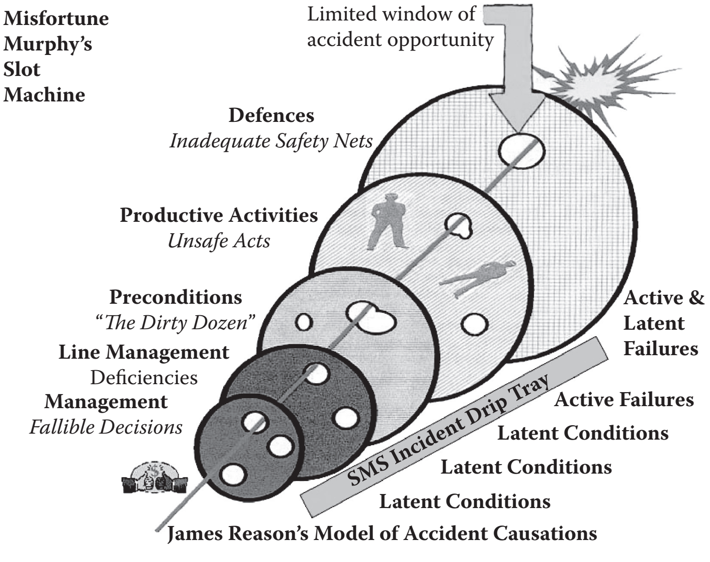


FIGURE 3.5 (See color insert.)
The Swiss cheese model for accident causation. (Adapted from the G. Dupont modification of Murphy's slot machine (diagram originally by James Reason). Online at: www.system-safety.com/trainingvideos/Training_Aids/Misfort ue%20Murphy/misfortune_murphy.htm)

failure. The holes in the various slices may be mobile or static. In the event that a series of holes in the slices of cheese line up, an accident trajectory will pass through corresponding holes in the layers of defenses, barriers, and safeguards, exposing hazards to people, assets, and the environment.

On the way home, Rob wondered how this particular HTF system had evolved to a point where there was no effective control system. Could this be so?

- The automatic control system provided paths to increase HTF temperature, rather than monitor and find the reasons for decreasing heat transfer rate.
- No analysis of abnormalities in the system or the HTF itself was present in the recent history of the plant—"Set and Forget."
- Design changes were made to the HTF system without HAZOP or other analysis of the effects in operation. No change control was evident.

But what were the drivers of this lack of control?

His mind went back for some reason to the managing director's visit this week, a visit that had passed him by. But the management summary was in his "to read" folder and couldn't be escaped. The headline messages were:

> "Next quarter's results are really important for the company. Let's focus on this."
>
> "Production cost is too high. You need to reduce it."

And then:

> "We have to move faster on improvements. If something's not working, then fix it."

Rob hoped the last exhortation didn't mean that causes of variation could remain hidden because we didn't have time to find them. The essence of control was removing those causes of variation one by one. Without this process, there would be a gradual breakdown in control and erosion of performance and safety over time, until you didn't know where to start, and every day brought new unpleasant surprises like the one that Rob had just been through.

Exercises

1. Explain what you think was the immediate cause of the HTF accident that happened. What was the root cause?
2. Using the Swiss cheese model in Figure 3.5, what are the two defenses that were present in the design of the HTF system and the control of the HTF itself?
3. Using the same model, what was the role of line management (the fallible decision) in creating "holes in the cheese," in other words, latent conditions that eventually led to the accident?

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4

Industrial Accidents

"What a waste of time. I've got enough going on." Rob was burning as he drove the veteran plant manager, Holden, through the gate and out onto the smelter road.

After the HTF fire investigation, the plant manager had said, "Rob, I'd like you to take a couple of days offsite. There's a course on Plant Hazard Analysis that I want you to attend. You're booked on it. It's at 10 a.m. next Monday at the Novatel in Auckland. Be there."

That was all she wrote.

As usual, the drive along the empty straightaway was soothing. "What could be gleaned from the mistakes made by other people in other industries? What would they know about the complexity of aluminum plants? "

At the course, Rob's discomfort was like a distress beacon for the instructors.

"But, is aluminum production really different from other process industries?" one of the course instructors, Tony Alderman, had asked. "Let's look at it, Rob. A smelter has multiple reactors, heating systems that can get out of control, right? There are control systems that are based on proportional control back to a target value, using the deviation from the target. These controllers respond to variations caused by things such as a change in feed or fluid properties, or a change in the rate of heat transfer across a surface, a variation in the procedure or process, a change in the equipment design, or anything else that might give rise to a deviation, such as a change in the process target itself. Right, Rob?"

"How much does this guy know?" Rob thought. He felt the color in his face rising as he met the friendly gaze of the instructor and the rubbernecking eyes of the other participants. You could sell tickets … and they had.

"Yeah, that applies pretty much in milk processing, too," Jim, a milk production manager commented.

"Actually, every tank and pipe is a reactor, because the milk is alive with bugs. Each batch is different, and if you leave some of the last batch in a tank, the whole lot can go off. However, you won't find out until it's too late because we don't have online sensors for that."

That was like a call to arms.

There were methanol as well as gas production people there, a gold mineral processing superintendent, one or two steel makers, and a larger number of plastics forming and molding technologists. The inquisition became a confessional.

All kinds of common plant characteristics began to emerge during the day. Unit operations were the same wherever you went—crushing lump feed materials to the right size distribution, heating or cooling liquids on heat transfer surfaces, compressing or just handling explosive gases, quenching cold feed materials into hot reactors. And most operations seemed to be performed and controlled with roughly similar characteristics.

Just like dairy factories, breweries, oil and gas plants, steel or plastics manufacturers, and aluminum production all required complex materials contacting and processing equipment that got a variable amount of maintenance attention (usually "the squeaking wheel gets the oil" type of attention). All the plants represented had a shift workforce that operated continuously with intermittent information flows or sometimes none at all, such as the gold mineral processing. All tried to automate processes, but the control systems were not set up to identify or remove causes of variation; rather they were there to keep the process at its target whatever the underlying problem was. In these automation systems, there appeared to be an absence of guidance or tools to even attempt to find the basic causes of the variation. It was just not part of the plan.

As participants, each had his/her say. Rob sketched out the smelter flowsheet on his notepad, something he had never had time to do before. The process of aluminum production was broken down into discrete manufacturing units: raw material storage, green anode production, anode baking, anode rodding and butt cleaning, electrolysis of alumina in the potlines, bath processing to cell cover material, dry scrubbing of the potline gases and recycle on the alumina, and the casthouse for solidifying the molten metal into shapes.

Laying it out this way, Rob saw most of the same unit operations as in the other industries. Aluminum production was just another combination of the same materials handling, processing, and manufacturing steps. Of course, one step affected others, sometimes in subtle ways. Anything you did in the carbon plant—right from the dry aggregate preheating step in green to anode stub casting in rodding—had a profound effect in the potroom, if you could diagnose it, of course.

With a start, Rob saw the connection between his plant's accident and the quality of the anodes and later the stability of the potroom. However, that was like the tip of the iceberg. What about all the times that the aggregate preheat temperature or the pitch target temperature had not actually been reached, because of the same set of HTF (heat transfer fluid) system causes that eventually led to the accident. *Process safety and process performance were really one and the same thing.* This made the lack of HTF system knowledge even harder to accept.

But, then, the recent case of a "sick" pot in the reduction lines surfaced in Rob's mind while he listened to the accidents of the course participants and how they had occurred. A pot had got to 1075°C and was completely out of control. Many extra anodes were destroyed trying to keep it in operation, and the potline bus bar was damaged and almost cut by the liquid metal tap out that occurred when the pot finally failed. It should have been shut down before any of this damage occurred. Several operators had sustained minor burns and muscle strains during the struggle to keep the pot in operation. Wasn't that the same management behavior as "keep it going whatever the cost?"

Smelter Flowsheet

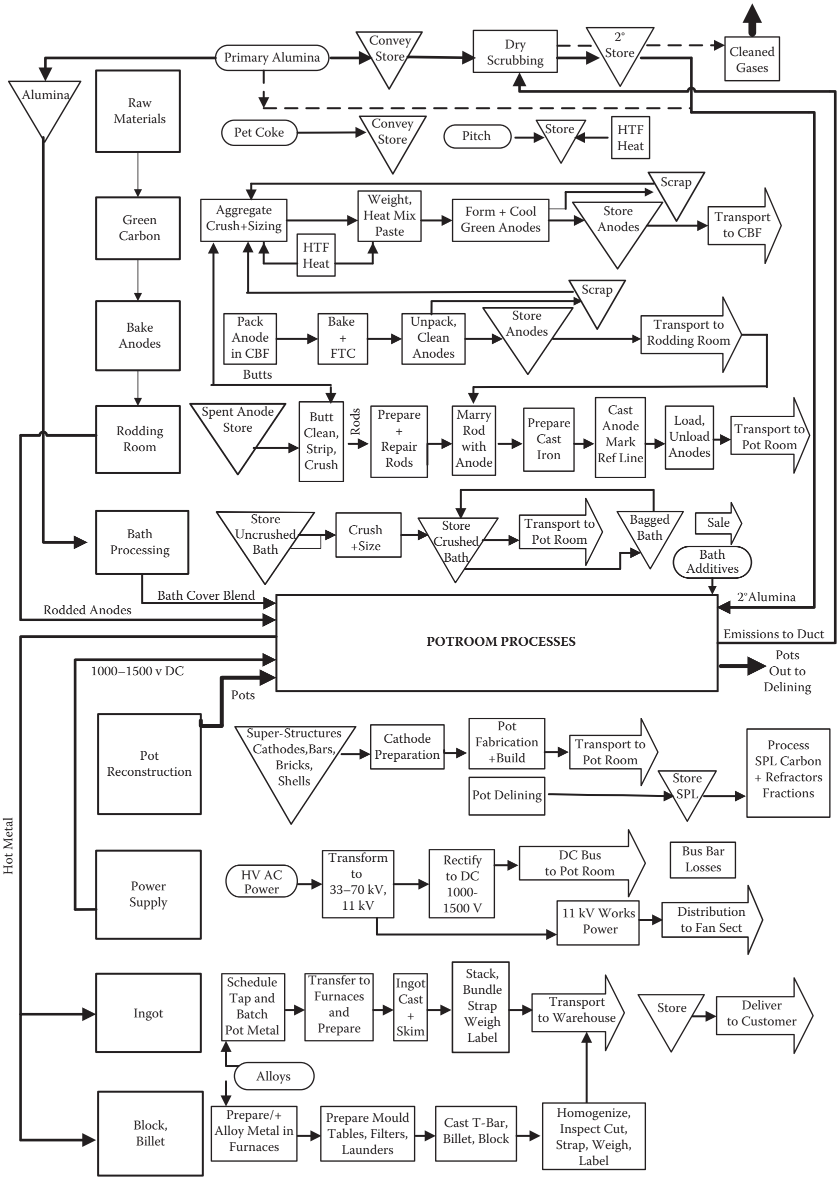
The central block of the smelter flowsheet (Figure 4.1) contains the process of producing metal through electrolysis. This "potroom processes" flowsheet is carried out on one or more potlines and will be discussed in detail in the following chapters.

A complicating factor in the potroom processes block is that there are many processes that occur simultaneously in the same reactor or "pot," as it is known in the industry. Most of these processes occur within the electrolyte itself that is superheated only 5 to 15°C above its primary crystallization temperature. The bulk cryolite-based electrolyte is "acidic" with an excess of aluminum fluoride (8–13% mass) over and above the cryolite composition. An almost pure cryolitic layer freezes on the sides of every pot as "ledge" that protects the walls from failure and balances changes in the surplus heat generation in the pot with the heat transfer through the sidewalls.

However, there is a different electrolyte composition within the high alumina, sludge material that is deposited on the cathode surface as a result of poor alumina dissolution and the anode setting process. This cathode sludge material is a two-phase mixture of alumina-saturated cryolite (with a small excess AlF3 content of 2–5%) and a mass fraction of 40 to 60% undissolved alumina. The bath phase will freeze on the cathode at temperatures below 940 to 945°C, unless there are substantial concentrations of other alkali fluorides in the bulk electrolyte (lithium or potassium).

In contrast, the electrolyte material that is within the top crust of the pots has a more acidic composition than the bulk electrolyte, more approaching the *chiolite phase* than cryolite, and with a melting point between 700 and 800°C, causing the crust to melt progressively if the top of the pot is overinsulated or the composition of the crushed bath forming the crust is allowed to move toward pure chiolite.

These thermochemical processes are not usually considered in the determination of the pot operating targets: temperature, composition, thermal profile (metal level, cover level, bath level), and alumina-feeding strategy. This causes a practical problem in most pot technologies because decisions to reduce bath temperature, increase cover depth, increase metal height, or change alumina feeding strategy do not take into account the interaction of the resulting pot thermal balance and temperature profile with these



SMELTER FLOW SHEET (many recycle streams not shown)

FIGURE 4.1
Smelter flowsheet showing main processes, with the "black box" of potroom processes to be described in detail later.

thermochemical processes (particularly cathode sludge solidification and crust melting), which are fundamentally linked to pot operation through the distribution of electrical current in the cathodes and anodes respectively.

Aluminum production was not that different from the other industries, Rob thought, as the conversation in the room continued.

The exception, though, was the pot itself, where there were a large number of materials and energy transformations occurring in the same physical location and within the bath. No wonder the composition, temperature, and volume of bath were continuously changing over time. The potroom processes also affected each other through this variation in the bath and, therefore, were tightly coupled and almost unobservable within each pot.

"Sort of like a continuous fermenter," the brewing manager commented. "We have fermentation, gas generation, and stirring, along with heat transfer processes all occurring simultaneously and at varying rates in the same vessel. We can't dictate the production rate because it is determined by the temperature and the yeast conditions."

"Or a direct iron ore reduction kiln," the steel technology guy said. "The titanate and other impurities in the ore change the way it flows through the kiln during the prereduction. It can actually block the whole kiln if you're not careful."

Yeah, Rob mused. But how many of those reactors did one plant have—two or maybe three? For sure, it wasn't 500, like a smelter.

The expert accident investigator asked, "Okay, are we on the same page?" He was building up to something, Rob thought.

"What is the thing that keeps you awake at night?" There was silence. It was not something this group of production managers and engineers even wanted to think about, let alone give voice to. Rob had experienced it, all right. The 2 a.m. phone calls and the HTF explosion were raw memories stalking his sleep.

"Then let's consider some situations that come into the category of nightmares for production managers, shall we? At least we know these won't come back."

The litany of human disasters was revealed. Rob had heard of some of them: the oil rig Piper Alpha, the pesticide plant Bhopal in India, and the Esso gas plant at Longford, Victoria. But, then, there was Flixborough, the Nypro plant in the United Kingdom; Seveso, a herbicide plant in Italy; and the polythylene Phillips 66 plant in Pasadena, Texas. Countless other oil refineries, rigs and volatiles storage facilities, metal powder plants, and steel plants were on the long list, but, mercifully, the course ended first.

Why Do Accidents Happen?

Accidents do not just happen; there are always "signs" that are not acted upon, in addition to inadequate health and safety measures in order to meet financial targets, and the authority not having sufficient focus or capacity to monitor progress and act accordingly.

A Royal Commission of Enquiry[1] into the Pike River Coal Mine disaster in New Zealand on November 19, 2010, which killed 29 people, found that "… In the last 48 days before the explosion, there were 21 reports of methane levels reaching explosive volumes, and 27 reports of lesser, but potentially dangerous, volumes. The reports of excess methane continued up to the very morning of the tragedy. The warnings were not heeded."

The company had only one mine, and it was the sole source of revenue. Hence, it had to borrow money to keep operations going. The company projected more than a million metric tons of coal being produced by 2008, but only 42,000 metric tons of coal were shipped in total by 2008. "In the drive toward coal production, the directors and executive managers paid insufficient attention to health and safety and exposed the company's workers to unacceptable risks. Mining should have stopped until the risks could be properly managed," according to the commission. "The Department of Labor did not have the focus, capacity, or strategies to ensure that Pike was meeting its legal responsibilities under health and safety laws. The department assumed that Pike was complying with the law, even though there was ample evidence to the contrary. The department should have prohibited Pike from operating the mine until its health and safety systems were adequate."

These findings are déjà vu as the following quote by Krause[2] shows with reference to the BP Deepwater Horizon catastrophe of April 2010:

> Senior executives within the drilling organizations failed to establish a culture that supports the risk analysis, understanding, communication, and decision processes needed for adequate operational safety and reliability. Government regulators failed to set adequate safety standards and enforce compliance. Both failed to heed warnings of problems, act on the knowledge of problems, and failed to prepare adequate response plans because they underestimated the worst-case scenario.

These excerpts also demonstrate that production systems driven by economic or other performance indicators require not only *Controls,* but also *Audit,* in order to achieve and maintain a level of control-giving safe outcomes. A production company must close its process management loops to prevent fatalities. But, these *Controls* that are put in place by the production organization will ultimately degrade over time or degrade due to external pressures if they are not *independently audited* on a regular basis. In terms of safety, an important audit function is provided by external organizations, e.g., government agencies.

The auditing agency (or auditor) can never prevent a single failure in the control process of a production company, unless it can audit 24/7 at the rate of every second. What it can do is ensure that control processes have integrity in measurement, in visibility of signals, and in the certainty of management response to minimize control failures in the future.

Therefore, the central issue addressed in this book is the design of the control system itself, so that the signals/triggers for action are identified and causes of variation can be exposed and addressed. This underlying design is really part of the production system itself and is dependent on a deep understanding of the control objective and mechanism especially in regard to human decision making. This understanding will allow meaningful *Controls* or measures to be put in place by any production organization, and for these controls to be *auditable,* so they remain operational over time, despite the difficulties that businesses and other enterprises go through.

Human Factors in Accidents (Events)

Names, such as Piper Alpha, Bhopal, Flixborough, BP Texas City, Buncefield, Esso Langford, and BP Deepwater Horizon, are widely known and linked to major industrial accidents that resulted in loss of life, revenue, environmental damage, and increasing distrust of technology and big corporations by society in general. Analyses have shown that there is at least one very important common thread that contributed to these accidents. Many, including Kletz[3], and Lardner and Nicholls[4], considered the human factor aspects. Human factors or human errors have been the subject of a number of books (see, for example, Mill[5], Reason[6], Kletz[7]).

The U.S. Department of Energy's *Human Performance Improvement Handbook*[8] (Figure 4.2) shows that 80% of *events*, and close to 90% in some industries, are attributed to human error, where an *event* is defined as "an undesirable change in the state of structures, systems, or components or human/organizational conditions (health, behavior, controls) that exceeds established significance criteria." The remaining 20% involve equipment failures.

Within the 80% human errors, it was shown that about 70% are linked to events that were classified as latent organizational weakness, which were "perpetrated by humans in the past that lie dormant in the system," with the remaining 30% being caused directly by the workers. These events,

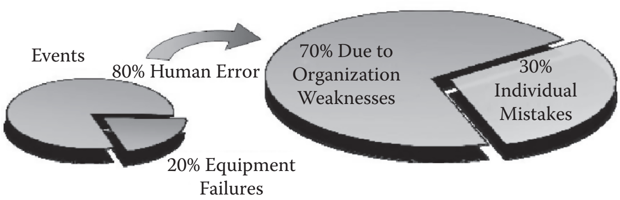


FIGURE 4.2
A breakdown of Unsafe Event causal factors from the U.S. Department of Energy's Human Performance Improvement Handbook.

within the 30%, may be compared to what are described by Reason[5] under the topic of unsafe acts, unintended and intended, which include slips, lapses, mistakes, and violations. Ghosh and Apostolakis[9] gave examples of latent organizational weaknesses, and these include "inadequate training is not revealed until an incident where that aspect of training was required; procedure deficiency not revealed until a particular step is required; work-arounds may be fine most of the time, but in sporadically challenging situations more formal procedures are needed and not used."

In fact, even the 20% of events due to equipment failures are very likely to be caused by latent organizational weaknesses, e.g., in the application of a maintenance system. Similarly, analyses of unsafe acts by safety practitioners such as DuPont have found that a high proportion of these are driven by the leadership of the organization—or lack of it.

The link between these latent organizational weaknesses and human factors has been investigated from a psychological standpoint to identify deeper causes.

Roberto[10] analyzed the 1996 Mount Everest tragedy where five mountain climbers perished. He examined the interaction of cognitive bias, psychological safety, and system complexity. A summary also is given by Krause and Timmins.[11] It was clear that the tragedy was not due to one single cause but, instead, numerous causes including leadership, team functioning, and flawed decision making within a complex system interaction, in a manner very similar to what occurs within an organization. Three types of biases were particularly noted:

1. **The Sunk Cost Bias:** People tend to make choices that support past decisions and escalate their commitment to a course of action they have invested in, even when there are contradictory data.
2. **The Overconfidence Bias:** People tend to exhibit overconfidence when they have abundant data that they believe are true, even if they have not been demonstrated to be true.
3. **The Recency Bias:** When making decisions, people tend to pay more attention to data that are recent and easy to recall.

Krause and Timmins[11] stressed the importance of recognizing and understanding cognitive bias and listed the following more common ones.

- **Anchoring**: Giving disproportionate weight to the first information received; initial information anchors subsequent judgments
- **Attribution**: Associating success with personal ability and failure with bad luck or chance
- **Fact/Value confusion**: Regarding and presenting strongly held values as facts

- **Overconfidence effect**: Feeling overconfident in the face of an abundance of data
- **Order of effects**: Remembering data more easily at the beginning and end
- **Recency effect**: Being partial to data that are most recent and easiest to remember
- **Redundancy:** Increasing the confidence level as the data become more redundant
- **Rosy retrospection:** Looking back and remembering the "good times"
- **Sample bias:** Placing high value on a small sample that is flawed due to inadequate sampling technique
- **Selective perception:** Seeking data that will confirm your views
- **Status quo bias:** Preferring alternatives that support the current conditions; it's a safer strategy and involves less personal risk
- **Sunk cost effects:** Making choices that support past decisions, even when the choices appear no longer valid
- **Wishful thinking:** Preferring the decision because the outcome is desired

The reader is encouraged to look up Roberto[10] and Krause and Timmins[11] for the details.

The latent weaknesses or pathogens created by the interaction of these human factors in decision making within a production process form the holes in the Swiss cheese in Reason's model presented in Chapter 3.

Then, it is only a question of when the holes lines up to defeat the multiple protection layers.

Despite the air conditioning, Rob's shirt was stuck to his back, and there was an ache behind his eyes. So many people killed outright. So many more poisoned or permanently injured. Lives and families shattered. For production of what? Is this what lay in store for all production managers?

Rob walked onto the plane in a daze. His mind was spinning. This might be the harassed, production look that he had seen before but not really understood.

Extracting the course folder (ref. Managing Risk and Reliability of Process Plants, Tweeddale, 2003) from his briefcase, Rob started to list some factors about the major accidents he had just relived. It seemed that once a situation reached a certain point, it became inevitable that damage would result, and then it was a matter of the plant design, who was on site, and chance. Like the HTF explosion, Rob thought grimly.

However, were there some actions or conditions before this "metastable" moment which consistently led to a situation where things could get out of control so that accidents would likely result?

Rob's List of Actions and Conditions that Lead to Out of Control situations

A. *Process abnormalities in operating plants not detected or diagnosed, including serious incidents that should have acted as warnings.*

Instead, the control systems led to a very large number of alarms being triggered by comparison of signals with specifications, although there; nothing abnormal about the signal itself was it being within the normal variation to be expected. After a while, these alarms just get acknowledged because a cause and a solution cannot be found. Positioning of visible alarms and their lack of specificity to a particular problem are also control design issues here.

B. *The basis for the plant flowsheet and equipment design not "refreshed" or well understood by the staff onsite.*

HAZOP studies fulfill this function normally. Lack of this refreshment process can lead to reductions in the complement of operating equipment or in the operating/maintenance staff for them. No one can explain why the existing extra equipment or procedures are necessary. So, cost reductions are made. This is not only a training issue but also an absence of formal hazard studies and change management processes. Thus, the plant design itself or its operation can be subtly altered without understanding of the potential effects (latent errors) as the plant adapts to different economic conditions and loss of experienced staff over time.

C. *Operations management unwilling to shut down equipment or the plant on the basis of out of control or unknown conditions.*

Driven as much by a "try until you succeed and don't ask for help" operating culture as by formal production targets, but leadership plays a part here. For example, unwillingness to shut down a pot that has lost temperature control (even though at 1075°C). Eventually this leads to unsafe situations and actions that make the plant more dangerous, and then an accident.

D. *A natural process of gradual loss of operating procedure compliance over time …*

… with undiagnosed variation increasing due to absence of human protocols and controls designed to support the limited functionality of the automatic control systems. This includes lack of an effective Safety Management System with auditing of safety, incident reporting, and controls and management review of the operating and maintenance practices.

E. *Inability to diagnose latent or embedded errors in the control and design systems in the plant, such as in fail safe protection systems that are seldom operated.*

These errors, therefore, can remain and eventually enough such errors align to produce a chain of events leading to an accident or process failure. Effectively it is the duration or lifetime of each latent error that makes this alignment or "Swiss cheese" effect inevitable. Therefore, periodic, detailed "what if" audits involving experts as well as production staff and documentation and removal of latent errors are crucial (and sometimes missing) steps in production facilities. These are sometimes incorporated into safety auditing processes, but the level of detail needed to pick up many latent errors in control systems is higher. Other compulsory maintenance checks, such as actuating protection systems on a regular schedule, also are necessary to limit lifetime of latent design and control errors in production systems.

Rob looked at the list, and thought about the HTF accident.

Combined with absence of investigation of abnormal events and warnings (A), point (D) could lead to continued decay of operating and maintenance standards until out of control situations eventually prevail: the HTF oil flash point deterioration and the lack of cleaning of fouled heat transfer surfaces in this case. Then, the production culture and/or company policy, point (C), would likely prevent shut down and bring an unpredictable situation to the point of being dangerous.

There were warnings with the HTF system, and, even before it exceeded the minimum allowable temperature of 140°C, there was a trend in HTF flash point that was not recognized because a lot of the data weren't recorded properly or plotted so people could see them. So, that was point (A): Creating the conditions under which problems would not be picked up.

Then, there was the maintenance practice on the aggregate preheaters and pitch heating equipment. Why was the heat transfer resistance between HTF and dry aggregate or pitch allowed to increase over the past few years? This is really about the plant design basis in terms of the rate of heat transfer. It seemed that no one, right up to the manager, had understood the way an HTF-based heating system worked. The system was "set and forget," a comic phrase that was now burned into Rob's brain. So, that was point (B). The unperturbed process design was not understood, even at the simplest level.

However, the more subtle aspect of the plant design was the "improved" vent pipe position on the HTF tank. This was still point (B) above. But, would Rob have picked this up himself? He had not done so during the investigation, and there had been no "what if" audits to give the operating and maintenance teams the chance to find this embedded error. That was point (E). Without this periodic audit of design and control systems, the only possible protection for the plant in this situation was a rigorous change control procedure, and there wasn't one.

Then, what about the control practice that allowed the target HTF temperature to be increased again and again, rather than looking for the cause of the reducing dry aggregate or pitch temperatures? Hence, this was point (D), in spades. The automatic control system was allowed to do its thing until it exceeded the safe limits of the oil.

The facility could still have been shut down on one of the shifts when the operators saw the extreme HTF condition. This would have meant shutting down green anode production, of course, which would not have been popular and was not authorized by the manager. Thinking back to the investigation, the operators had discussed changing the oil with the superintendent. Thus, point (C) had acted to prevent a shutdown before the accident.

An eventual explosion was not preventable after this. The ignition source had never been found, and the life of the maintainer was in the hands of chance.

Rob looked further into his course folder and another picture caught his eye. It was the Det Norske Veritas (DNV) Loss Control Approach (Figure 4.3), relating specifically to incidents that cause loss—accidents, in other words.

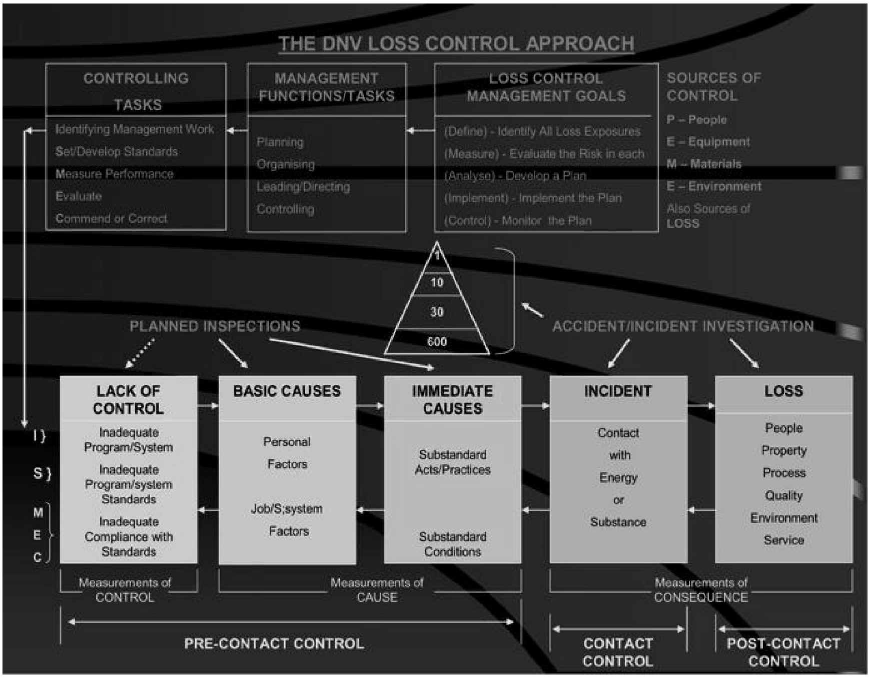


FIGURE 4.3
DNV Loss Control Approach to Accidents, showing the connection with process control and management. (From Bird, F. E., Jr., and G. L Germain. 1996. *Practical loss control leadership*, revised edition. Houston, TX: Det Norske Veritas (USA). With permission.)

Was it the 737's altitude …, or did this look exactly like the diagnosis of a process control failure? And, it led all the way back to the *Lack of Control (Management Goals)* box. That was where prevention of accidents and also control of production and plant both started. And this box was the responsibility of management—which was Rob. Not the operators and not the maintainers, not even the superintendents.

The production manager was the only person authorized to change a management system related to production.

Exercises

1. Using Rob's List of Actions and Conditions leading to out of control events (Points A to E) in this chapter, identify three of these points that apply in the Esso Longford Gas Plant Explosion in 1998, which is discussed in Appendix 1 below (with permission of Andrew Hopkins, Australian National University, Canberra).
2. Look at the DNV Loss Control approach to accidents in Figure 4.3. What box does each of your identified failures fall into?

Appendix 1: Lessons from Esso's Gas Plant Explosion at Longford

Excerpts from Andrew Hopkins
Lessons from Longford: The Esso Gas Plant Explosion CCH Australia.
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Excerpt 1

In September 1998, Esso Australia's gas plant at Longford in Victoria suffered a major fire. Two men were killed and the state's gas supply was severed for two weeks, causing chaos in Victorian industry and considerable hardship in homes that were dependent on gas.

What happened was that a warm liquid system (known as the "lean oil" system) failed, allowing a metal heat exchanger to become intensely cold and, therefore, brittle. When operators tried to reintroduce warm lean oil, the vessel fractured and released a large quantity of gas that found an ignition source and exploded.

Excerpt 2

The Failure of the Alarm System

Operators at the Longford plant were required to keep operations within certain parameters (temperature, volume, etc.). When the process went outside these parameters, alarms would both sound and light up on control panels. The sound could be, and was, silenced immediately, but the visual indicators would remain until the process returned within the specified parameters. In practice, alarms were very frequent—hundreds and sometimes thousands every day. It was clearly impossible for operators to monitor these alarms, let alone respond to them, and they had become accustomed to operating the system in alarm for long periods. Operating in alarm mode was tolerable in some circumstances, but operators had no way of distinguishing critical alarms from nuisance alarms. The result was that operators became desensitized, and alarms consequently lost their capacity to serve as warnings. It was the failure to respond adequately to these alarms that led to the failure of the lean oil system, which in turn led to the cold temperature embrittlement of the heat exchanger.

Other disasters have been preceded by a similar process of normalizing the warning signs. Prior to the Challenger Space Shuttle disaster, there was evidence that the so-called O-ring seals on the booster rockets malfunctioned at low temperatures. However, previous launches at low temperature had not ended in disaster, and so the malfunction had come to be accepted as normal. On the launch date in question, the atmospheric temperature was even colder than usual, but the expected malfunction had been normalized, and the launch was given the go-ahead. On this occasion, the O-rings failed totally with catastrophic results.

Similarly, prior to the Moura mine disaster in central Queensland in 1994 in which 11 men were killed, warning alarms had become so frequent that they were regarded as normal and so discounted (Hopkins, 1999).

Excerpt 3

Conclusion

This paper has analyzed the findings of the Royal Commission into the major accident at Esso's gas plant at Longford in Victoria in 1998. In the process, it has identified a number of lessons that are applicable to hazardous industries, generally. It is appropriate to summarize those lessons by way of conclusion.

1. Operator error is not an adequate explanation for major accidents.
2. Systematic hazard identification is vital for accident prevention.
3. Auditing must be good enough to identify the bad news and ensure it gets to the top.

4. Reliance on lost time injury data in major hazard industries is itself a major hazard.
5. Good reporting systems must specify relevant warning signs. They must provide feedback to reporters and an opportunity for reporters to comment on feedback.
6. Alarm systems must be carefully designed so that warnings of trouble do not get dismissed as normal (normalized).
7. Senior management must accept responsibility for the management of hazardous processes.
8. A safety case regime should apply to all major hazard facilities.

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Further Readings

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5

Potline Process Control Failure

Back onsite. The course was a distant memory. Rob was walking into Line 1 and looking at the familiar anode setting and tapping operations. They seemed to be on time, plenty of anodes and crucibles out on room A, and the PTM (pot tending machine) busy.

As he was walking through room B West, he noticed that there were some low temperatures on the risers. These pots carried sludge most of the time due to the alumina feeding system, and they needed temperatures in the 955 to 965°C range to keep it from solidifying on the cathode. On the way to his office, he counted 26 out of 52 pots below 950°C.

"The guys are seeing a lot of pots with high AlF3 due to the change in alumina, Rob," Ford said, referring to the slightly lower soda content of the last alumina boat that arrived over the weekend. As usual, the assumption had been made that the cause was not here but somewhere else.

"Let's have a look at the temperature, AlF3%, and other charts for each potline over the past month, shall we, Ford? Before we find someone or something to blame, I mean" (Figure 5.1)

Looking at the charts showing the past two months of average data for line 1, it was hard to see what might be any real changes or trends in the data. Questions came into Rob's mind:

- Was there a significant upward movement in the noise on the pot voltage?
- The average bath temperature didn't appear to have changed, from the chart, anyway. Was there anything about individual pots in different rooms that wasn't showing up in the average?
- Average voltage had increased at the end of last month, but was that across all the pots?
- On some of the charts, there were two horizontal lines present that seemed to be limits of some kind. What did they mean?

"Not too much happening there. These graphs are good at telling you what you already know." Having studied the data for long enough, Ford was now ready to ask Rob's question. "So, what are we going do, boss?"

For the many times Rob had heard this question, it never lost its motivational quality. Production was about action. That's why people liked it.

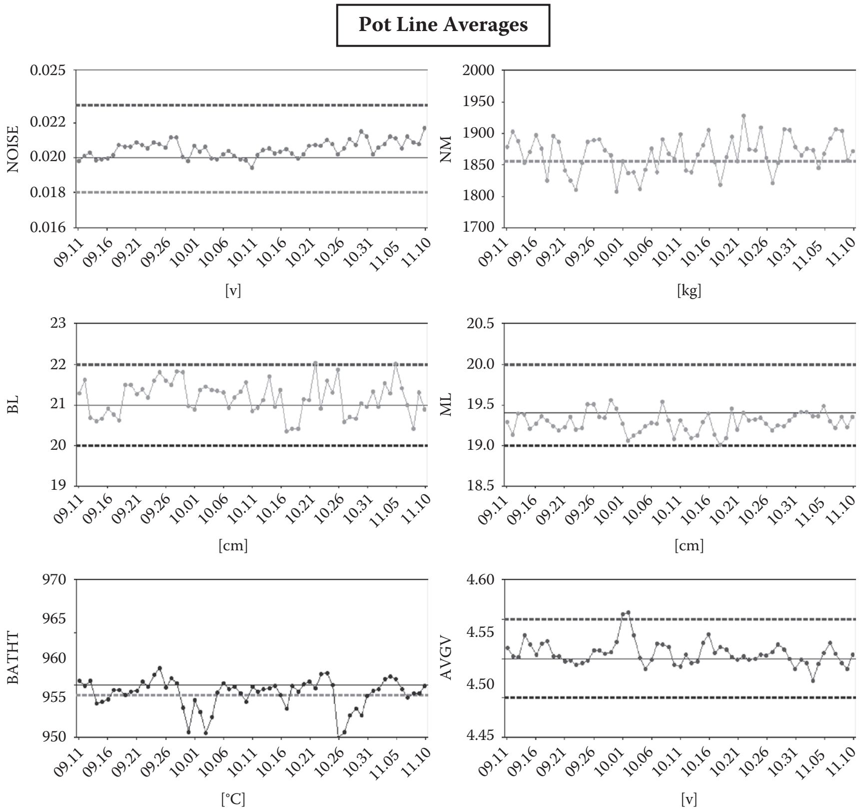


FIGURE 5.1
Potline 1 daily averages for (from top left) the Voltage Noise, Metal Tap (NM), Bath Height (BL), Metal Height (ML), Bath Temperature (BathT), and Pot Voltage (AVGV).

You got to do things, to react. The only thing was that the decision-making process was not exactly a scientific one.

"Well, how about we monitor the temperatures and chemistries more closely in the next week, Ford. I want to know what our individual pot-by-pot responses to this situation are and whether they are working."

Rob was left with the feeling that he was trying to grasp a jelly fish—too many unanswered questions. But, then, monthly production reporting time came, with tables of incomprehensible aggregated $ numbers, and the feeling passed.

Temperature and Composition Dynamics in a Potline

(*Refer also to Keith Sinclair's flipchart at end of this chapter.*)

Because of the large number of largely independent electrochemical reactors in a potline (always greater than 100 and usually greater than

200), the average of any parameter is a poor indicator of the degree of control of the potline. In fact, this is true of most production processes because there is no estimator of the variability within the process, other than that of the aggregated processes over time.

However, the situation in a potline is complex in another way: each pot is inherently different because of the unique way each has begun its operating life (start-up), the events and thermal shocks that have damaged it during its operating life, and the variation in raw and other materials to which it has been subjected over that period. The location statistics (the mean in this case) of each pot are very different and, in fact, the variance of the potline is dominated by the variance between pots for almost all operating parameters and performance outcomes. A chart of pot voltages on any day and even over a period of time is eloquent demonstration of this on any and every potline you can find. It is also important to recognize that the performance of the line is dominated by those pots at the extremes of the range.

The variance within each pot over time is also large, however, and this variation (e.g., pot temperature, composition, voltage, other) is generally not amenable to traditional SPC (statistical process control) models that rely on either a stationary mean or a mathematical description of the mean around which predictable variation occurs. Neither of these approximations is applicable to pots, unfortunately.[1] Both drift and cycling of the mean are observed depending on the heat balance conditions, and short-term variation shifts rapidly from small predictable changes to large changes due to discrete events, such as anode effect, anode problems, sludge accumulation, and disturbances to the anode or cathode current distributions.

These dynamic variations are describable in theory through formulation of the dynamic heat and material balance on a pot.[2] In particular, the thermochemical constraints on the bath temperature and cryolite ratio/XS AlF_3% variation have been quantified and are represented in Figure 5.2.

Pots that move outside of the above T/AlF_3% operating region do suffer process damage:

- Ledge loss and sidewall damage and possibly pot leakage: If extended periods (days) above 15 degrees bath superheat are sustained.
- Low current efficiency, high bath levels, and anode oxidation/dust: If a pot operates for extended time above 970°C.
- Cathode deposits and poor back feeding of sludge causing high AE (anode effect) frequency, current distribution problems, and unstable pot voltage: Extended time below 945°C.
- Risk of sludge buildup, poor alumina feed control, and difficult (low) bath level control: Bath superheats consistently below 5°C.

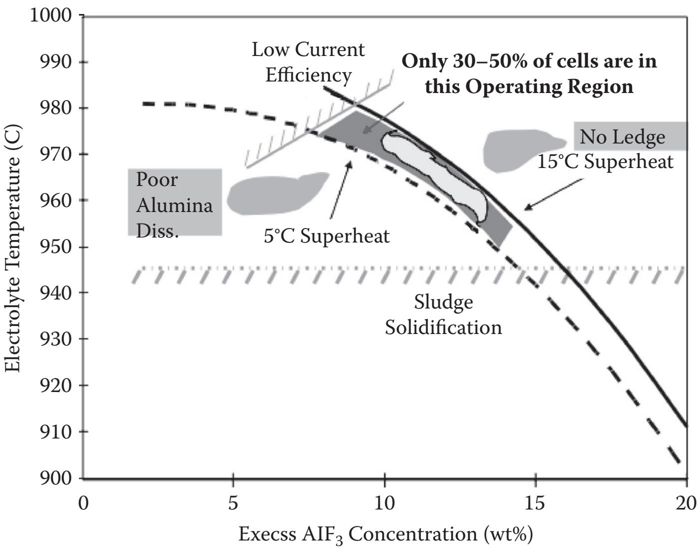


FIGURE 5.2
A bath temperature/AlF3% concentration slice through the multidimensional operating window for smelting pots.[3] This operating window shows lines of constant bath superheat, along with the sludge solidification line, and a line defining serious loss of current efficiency due to high bath temperature (and metal dissolution in the bath).

However, it is a fact that, at present, the best potlines in the world operate with a temperature standard deviation of 5 to 6°C and an XS AlF% standard deviation of 1 to 1.5 wt%. This means that at best 60 to 70% of pots will be operating within the optimum zone at any time, and, in practice, it is less than this because of the thermal disturbances caused by batch operations: metal tapping, anode setting, and variations in alumina feeding rate.

Efforts to control this natural variation in temperature and XS (in excess over the cryolitic composition) AlF3% produce frequent compensatory interactions by the pot control system, along with inappropriate targets for voltage and aluminum fluoride addition rate. These control actions actually magnify the bath T/AlF3% variation by affecting bath superheat through perturbing the heat balance or the primary freezing (liquidus) temperature of the bath. Inaccurate or unpredicted operating interventions by humans (e.g., taking more or less metal than the amount produced, adding more anode cover than required, allowing bath height to remain low or high) add another layer of variation, resulting in a chaotic process overall, with nonstationary mean. The wandering mean temperature and composition is the most serious problem in terms of damage to the process, because all of the damage associated with poor T/AlF3% control listed above is highly dependent on the time the pot spends outside its optimal operating region.

Despite these significant predictability challenges and, in fact, because of them, a more scientifically rigorous, pragmatic view of the variation on potlines does yield rapid improvement in the process stability. Examples of this approach are starting to emerge.[4] In these approaches, the detection and diagnosis of statistical abnormality in measured signals are the key levers in unlocking causal relationships and reducing variation from these causes.

Plotting the mean and range of the Line 1 data for one half of the potline (room A, in this case) for the bath temperature gives the following four-piece chart in Figure 5.3. Here, the X_bar – s.d (standard deviation) chart is given on the top right and, to the left, a box whisker of the potroom A temperature distribution is shown over the same two-month period.

Bottom left in the figure is the box whisker chart for each pot in the room, which is detecting pots that have different distributions, and, then to the right is a histogram of the temperature distribution in the room over the past week only. These four views allow some further stratification of the variation so that important types of variation (from the possible 5Ms and 1E) can be exposed as follows:

1. The control chart (top right) tells us that the temperature in the room has been out of control with 99% confidence (below the lower control limit on temperature) about one week ago. This means there is a real change in mean temperature.

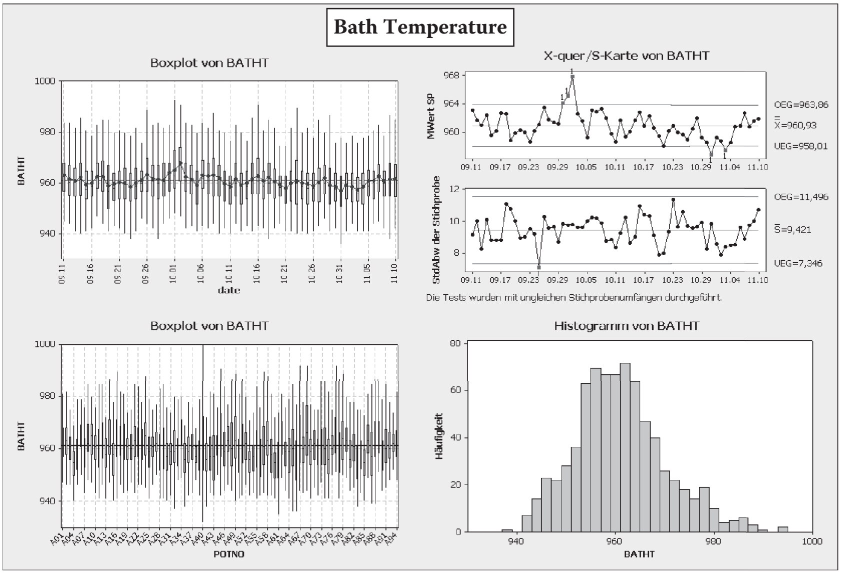


FIGURE 5.3
A "four plot" showing different views of the variation in bath temperature (BATHT) in Room A of potline 1,[5] including a control chart of the bath temperature (top right) and a histogram of temperature by pot for the last week of the period in the charts (bottom right).

2. The standard deviation of the temperature has been increasing for the past week as well. This is statistically an out-of-control signal because its 7/8 points are increasing in a row.
3. The entire distribution of temperature has been skewed to lower temperatures (middle 50% box of pots less than the long-term mean) for some weeks before this (box plot top left).
4. From the single pot box and whisker plots, consecutive pots on the line often form groups that are all low or all high in temperature, indicating possibly that there is an operational procedure or group feature like a crew, which may be influencing the temperature in these groups. Anode setting groups, measurement groups metals tapping groups, or alumina replenishment of the pot hoppers are examples of operations performed on pot groups, which can influence temperature.
5. The present distribution of pot temperatures in the room (histogram) shows that the bulk of pots are skewed to the cold side over the past week, but with a tail of very hot pots that may have some abnormal condition, such as cracked or spiked anodes. These hot pots also may be driving the increase in mean temperature and standard deviation over the past 4 to 5 days in the X_Bar – s.d. chart.

The cryolite ratios in this potroom (and, more generally, across many such potlines) show a similar pattern to the temperatures, although they are damped somewhat by the mass of liquid bath in the pot (4000–5000 kg). The slowness of the response of cryolite ratio should be a strong warning for all production staff also to respond slowly with changes in the AlF3 additions rate to each pot in order to prevent overshooting of the concentration of AlF3, and a corresponding magnification of both cryolite ratio and temperature variation.

In fact, the addition of aluminum fluoride to pots is necessary only to replenish the AlF3 neutralized by sodium oxide and calcium oxide in the alumina added for aluminum production. Therefore, large variations in the rate of AlF3 addition should not be required.

The reduction in mean cryolite ratio shown on room A in Figure 5.4 is probably the cause of the mean temperature reduction shown earlier.

The actual AlF3 additions driving the cryolite ratio trend are shown below for the same period for potroom A. The data show out-of-control variation in the mean addition from October 25 to 26, which is three days before the large decrease in mean cryolite ratio in this room. The cause of the reduction in mean temperature, therefore, is this AlF3 addition's action (possibly linked to the control strategy).

During the same period of rapid AlF3 additions, the standard deviation between pots doubles. It also is interesting that the mean addition of AlF3 increased as well at a time when the mean cryolite ratio was quite close

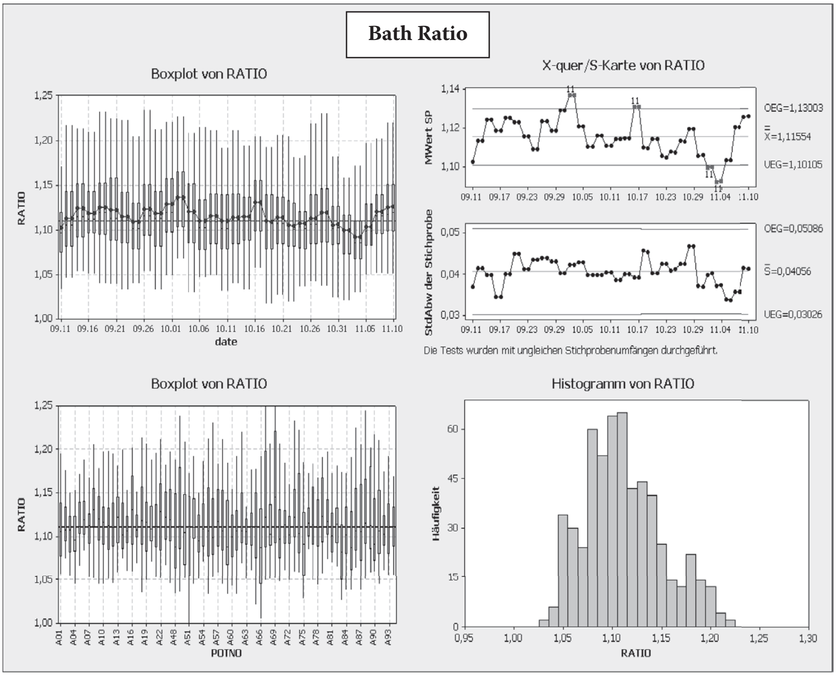


FIGURE 5.4
A "four plot" showing different views of the variation in cryolite ratio in Room A of potline 1, including a control chart (top right), histogram by pot for the last week (bottom right), and box and whisker charts by date (top left) and by pot (bottom left) over the period.

to the long-term average value. This may indicate a control strategy that overcompensates for small changes in cryolite ratio.

In Figure 5.5, the second box and whisker plot (bottom left) indicate that the largest additions over the past two months were made on several small groups of pots geographically situated. These large additions on specific pot groups are possibly a reaction to hot pots, but this is not indicated by either their temperature or cryolite ratios.

The premise that the high mean AlF3 additions and the locally high additions had anything to do with a change in the alumina quality (or soda level) is not correct, either in timing or in the nonuniformity of the response. It also appears that the individual pot additions may routinely be much larger than that required to move the cryolite ratio back to the target level. This conclusion is supported by the out-of-control oscillation of both the mean cryolite ratio and the temperature over the two-month period.

The type and magnitude of T/CR/AlF3 additions variability shown above are typical of most potlines, even of widely differing technologies. The reason for this is that the AlF3 material balance (and cryolite ratio) is habitually used to compensate for energy imbalances, as demonstrated in Figure 5.6.

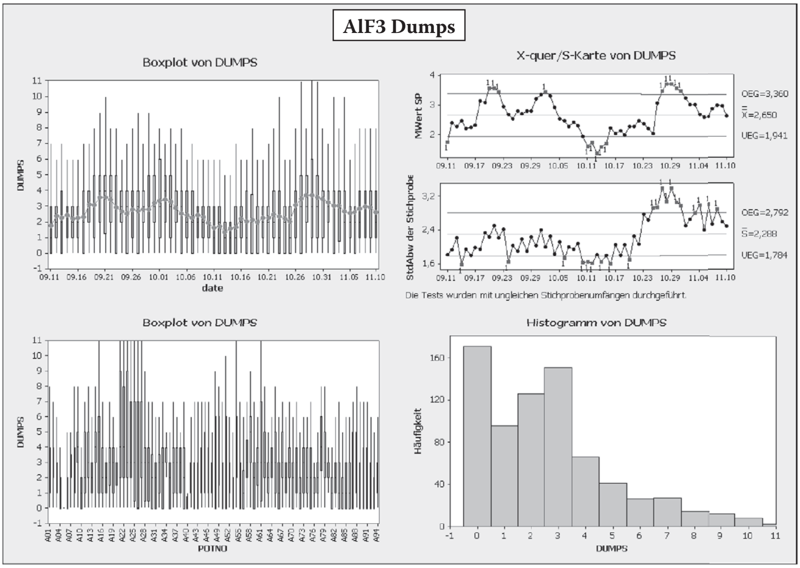


FIGURE 5.5
A “four plot” showing different views of the variation in daily AlF3 Dumps (kg) per pot, in Room A of potline 1, including a control chart (top right), histogram by pot for the last week (bottom right), and box and whisker charts by date (top left) and by pot (bottom left) over the period.

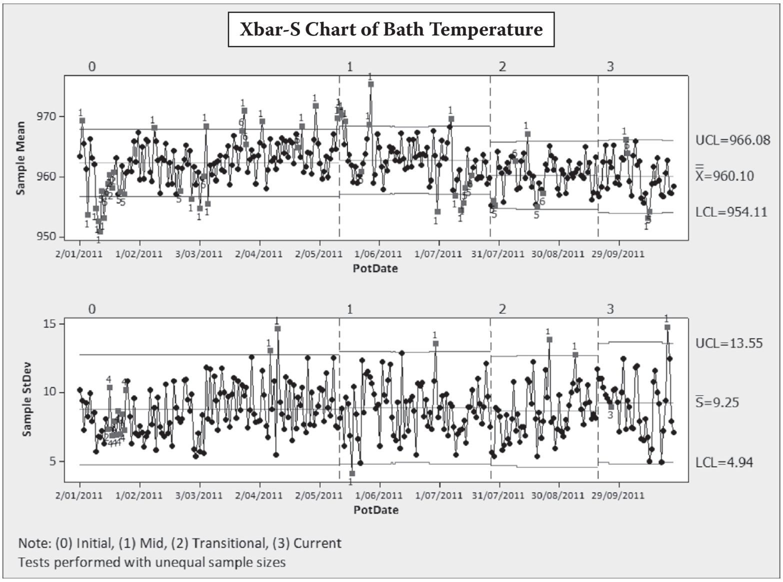
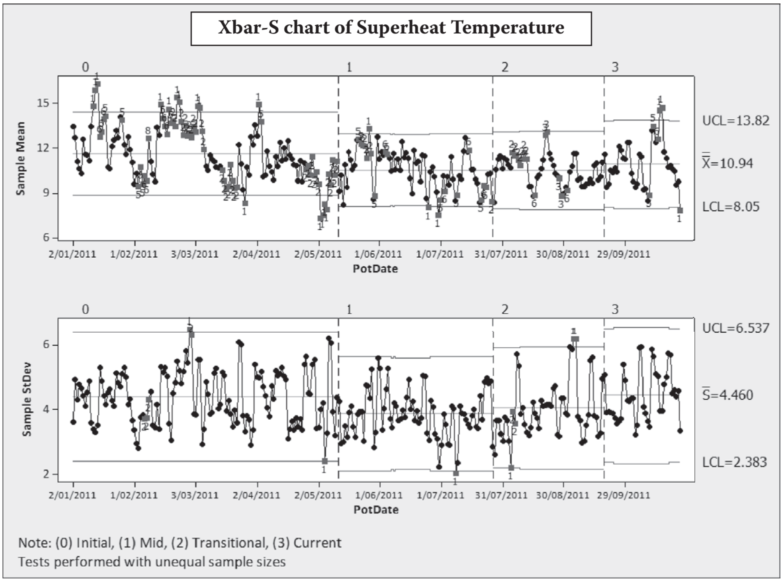


FIGURE 5.6
Bath Temperature Control Chart for potrooms A and B combined, showing the mean (X_Bar) and standard deviation (S) over a 10-month period.

The first X_Bar and s.d. chart show the temperature of the whole potline (rooms A and B) over a longer period of time. It is evident here that the mean temperature has been maintained in control over most of the period, although there are single days of high or low mean temperature. This degree of control is a consequence of the variability of AlF3 additions shown previously.

The chart in Figure 5.7 shows the mean of the calculated bath superheats for each pot based on their measured temperatures and cryolite ratios. The mean bath superheat is not in control and, specifically, the last out-of-control period in superheat is a sustained excursion and reaches 15°C, which is high enough to crack large anodes and cause damage to sidewalls. No change in mean bath temperature is evident, however. A large thermal imbalance has occurred, but the control response has suppressed the expected temperature change.

These increases in bath superheat cause bath volume fluctuation and will affect the performance of the anodes, including possible anode cracking and airburn due to cover melting. These effects are not necessarily the first to be seen, however. Another set of effects relates to overshoots in the temperature due to a very high AlF3 additions response, as shown in the previous chart. In the case of the subsequent low temperatures, alumina feed control can be lost on a large number of pots.


Xbar-S chart of Superheat Temperature

Note: (0) Initial, (1) Mid, (2) Transitional, (3) Current
Tests performed with unequal sample sizes

FIGURE 5.7
Calculated Bath Superheat Control Chart (using Solheim and Sterten equation) for potrooms A and B combined, showing the mean (X_Bar) and standard deviation (S) over a 10-month period.

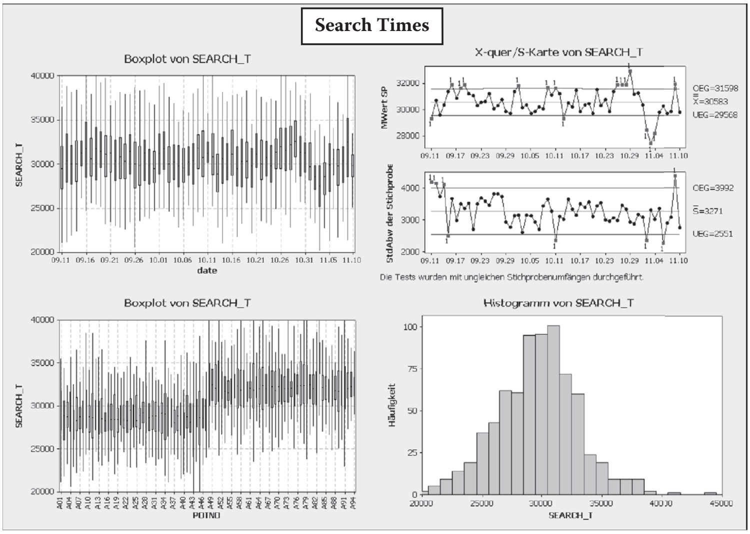


FIGURE 5.8
A "four plot" showing different views of the variation in average daily search time (search for alumina depletion in the bath), in Room A of potline 1, including a control chart (top right), histogram by pot for the last week (bottom right), and box and whisker charts by date (top left) and by pot (bottom left) over the period.

Figures 5.8 and 5.9 show the effect of the present temperature and cryolite ratio variation on the potline feeding process and the resultant voltage noise, which, in this case, is mainly cathode noise (rotating metal wave) related.

The drop in mean alumina search time on the first chart for room A corresponds exactly with the mean potline temperature reduction below the lower control limit in Figure 5.6 and the a lower temperature limit in Figure 5.3. Physically, what is happening is that alumina is not dissolving or not back-feeding from the cathode at the required rate. This causes low alumina concentrations in the bath and repeated low search times followed by overfeeding cycles that further build sludge on the cathode.

After this low temperature- induced alumina feed/sludging event, it is evident that the voltage instability or noise in this room is beginning to increase. This is very likely to be in response to the sludge on the cathode along with lower bath temperatures, and the additional effect of a reduction in ACD (anode cathode distance) due to lower alumina concentration and temperature may be important on some pots as well.

The noise chart in Figure 5.9 is typical of many potlines in several key respects:

- The mean daily noise values are quite low (0.020 μΩ) across room A, in this case. This is due to the averaging process that is part

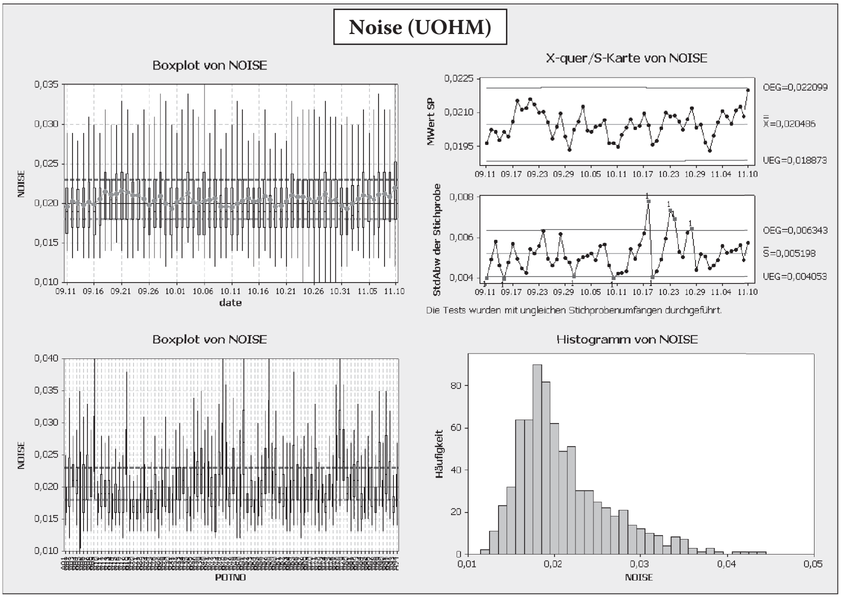


FIGURE 5.9
A "four plot" showing different views of the variation in average daily noise (measured as resistance amplitude), in Room A of potline 1, including a control chart (top right), histogram by pot for the last week (bottom right), and box and whisker charts by date (top left) and by pot (bottom left) over the period.

of the measurement. Voltage or resistance ranges over, say, one minute are averaged over five minutes and then over a day for every pot. So, any instantaneous or even prolonged noise events for 10 or 30 minutes are averaged out of the daily results reported in the smelter database. In fact the noise limits for "noise control" are usually in the range 80 to 150 ηΩ, or 0.08 to 0.15 μΩ, much higher when compared to the above scale.

- Comparing the pot-to-pot variation in the box plot, it is evident that there are some pots that have been extremely unstable over this two-month period, as well as a geographical group that has been very stable. Counting from the plot, there are 37 pots that have been extremely unstable for an unknown period during this two-month time span. The first observation tells us only that there is a second, unstable state for these pots. This state is very different from the normal, stable state of the process. This is why some control systems record and plot the Duration of Time Unstable (say, above 80 ηΩ), rather than the above time-averaged value of noise. Otherwise you are averaging data from two different populations (process states).

- The histogram of average noise for the potroom is a Poisson distribution. The tail of the distribution is long and far to the right, while the mode is skewed toward zero. This distribution is mirrored in many other potline distributions, such as pot voltage, and for the same reason. The second major state of a pot (high noise) produces electrical and often thermal disturbances that give it parameters far to the right (much larger voltage disturbances and actual voltages) than the time-averaged mean of the process. Parameters that are designed to be minimized in electrochemical and also chemical production processes—energy usage, electrical and thermal fluctuations, loss in yield or faradaic efficiency—all obey this type of distribution. Of course, the degree of "tailing" of the distribution is dependent on how much of the second disturbed process state exists.

Despite the insensitivity of the average noise parameter, it is signaling a significant change in Figure 5.9, and the Mean Search Time has signaled an out-of-control reduction in search times several days earlier and for the same reason; in fact, this is a leading indicator of the change in noise state of the potline.

Despite this signal, there has been no process response from Rob's production team, and this also is common in smelters. Out-of-control signals are only useful if they are detected and acted upon, and the present signals were not detected because no control charts were available to signal clearly that a loss of control existed. The charts available to the manager and superintendent (Figure 5.1) had only specification limits, and no measure of the distribution of the data about the mean for the potline. Therefore, there was no basis on which to judge the importance of a variation in the mean value in these charts. No decisions, therefore, could be made, and the eyes of the observers of these charts intuitively knew this.

However, this is not the only problem in creating meaningful process control charts, as plotted here for potroom A. A deeper problem is that even if the out-of-control event is detected, there is still a diagnosis process required to find the cause of the problem. In the present case, the first question should be whether the problem is an imbalance of mass or of energy. That is answered above by looking at the AlF3 additions. A mass imbalance has driven the temperature/CR changes.

However, beneath this it is possible and even likely that an energy imbalance exists and has driven early changes in cryolite ratio or temperature. The cause of this imbalance, if not removed, will possibly get worse.

Rob cleared away the mess of his monthly report calculations. It was a good month according to the figures. A high inventory of returned butts (where were they hiding last week?) and a low average electricity price had swung a –$5 million result last month to a +$3 million result this month. Rob wondered what this meant, or did it really mean anything? One thing the monthly report had done was to remove him from studying the production process itself. Was reporting all a manager was good for? He hoped not.

The next two weeks were a blur of crew meetings, mainly about safety, and managing the very useful "initiatives" of the general manager. Rob could not tell if this was time well spent or not. They were big investments of his time. Maybe a production manager had to accept this as normal. For sure, he had learned a lot by listening to the crews and not talking. That realization happened in the first crew meeting when no one said anything while he gave the "state of the union." He had glanced at the crew leader for help and Barry had fortunately come to the rescue.

" So, what do you guys really think? Jimmy, you always have a word to say on the risks out there."

"Yeah, I just want to know whether you're going to spend any money, Rob? We need some new tapping pipes and these remote controllers are killing the tappers' wrists."

That broke the silence and got a conversation going. But, every day away from the potroom process, the question resurfaced in his mind: How do I manage the process with the time that is left? The thought was lying in wait at the back of his mind again as he drove into the car park on a grey, cold morning. How do I solve problems for the crews? Where's the time that should be left for improvement, and where do I find the time if something else goes wrong?

It was just a feeling, but maybe that could be quite soon. He reflexively checked for some good news on his phone.

It wasn't that his phone didn't ring. Actually the volume was turned down to a level where it wasn't that easy to hear, but that was normal. Right? Well, it was normal now. Rob thought back to the seemingly omnipotent words of W. Edwards Deming, about listening to the process and detecting special causes that could then be diagnosed and removed. Where was Deming when you needed him?

Rob was walking down line 2 today on his way to the office. He wondered what had become of the low temperatures being reported a month ago. Now they seemed to be trending above average or higher. How many pots were normally above 980°C? Rob thought—an s.d. of 7°C and a mean of 960. So, there should be 1% maximum above 980°C, about 2 pots per potline. So why did he see 10 pots already, out of 30, so far on this bay? And that wasn't all. There were sights Rob couldn't remember seeing for a long time.

Cracked early change anodes parked up on the bricks by the dwarf wall; rounded pieces of bath impregnated anode (floaters) at the tap end of the pots; rows of unscheduled changes on the chain in the rodding room, spikes, and even some burnoffs that hadn't happened since the anode rod change-out here more than three years ago.

"We have some problems, Ford. When did this start happening?" Rob spoke directly to the point.

"Yeah, we got some stuff happening, Rob. But, we are managing it. Main thing is not to lose purity and keep the guys' heads up. Difficult things can happen out there. We just learn to get through it. That's all."

Rob watched Ford move away to the crew leader's office, talking to each operator with a smile and making a connection. If you had to be in a war, he was the right guy to be in it with.

The phone rang, or maybe it was just ringing continuously in Rob's office.

"Don't you answer the phone anymore?" The general manager's voice had a strident note.

"Yes, I was just out in the potroom, John. We have a few issues down here."

"You mean like 60 unscheduled changes per shift, and demand higher than the carbon plant can produce?"

"That high? We'll work on it, John." Rob was wondering if the problems in the actual potline were going to be mentioned.

"Okay, keep me up to date, Rob. This is getting expensive, and plant security could be at risk."…click and dial tone.

Rob picked up the phone and dialed a number from memory. The statistician he was calling was not onsite, but he had worked for the smelter for some years, and Rob needed him now.

"Tony, it's Rob. We have a problem down here. How soon can you get here?"

"Tomorrow, if necessary, Rob. I'm characterizing a certain variety of sea shells at the moment. But, they'll still be here next week." Tony's sense of humor was intact, and he was ready and willing.

"I want to understand why we can't predict trouble before we are in the middle of it, Tony. And, I need to know the answer before it happens again."

I'll be with you tomorrow morning, Rob. Who is my contact?"

"Ford will be your guy. I'll let him know to put you in the system. Your contractor pass is still active, right?"

"Yep, sure is, Rob."

Eliminating or Correcting Process Disturbances in Aluminum Smelters

There are a high number of process disturbances in smelters that can destabilize the entire operation, either with respect to the production, the purity of the aluminum, or the safety and health of people (Table 5.1).

TABLE 5.1

Common Process Disturbances, Signs, and Responses in Smelting Potlines

Issue/ Mechanism	Possible Causes	Earliest Signs	Triggers—Stop Now	Consequences of Loss of Control	Response to Avoid the Event	Response (Damage Limitation)
High Superheat (15°C +)	Anode problem in cell	T/AlF3 signal, anode noise or cracking	Red stubs across potline	Sick pots, pot tapouts/cut out	Fast anode identify, diagnosis	ACD, Metal Ht increases Extra pacman
	Dust	Dust in anode holes, C% in 2° alumina	Anode spiking or high T's	Serious cathode condition problems, plus sidewall failures	Keep # dusty pots (dust in anode hole) below 10%	Pacman every anode hole. Don't overfeed pots. Remove failed anodes. Keep bath up.
	Instability of voltage	Noise, Silicon in metal	Severe instability.	Pot failures – perimeter and sidewall.	Prevent overfeeding, op. track. Maintain AlF3 < 12%	Limit power input, track and reduce feed. Maintain AlF3% < 10%.
	High Alf3 additions	Bath generation. Higher AlF3%, without drop in Temperature.	Severe instability in 20% of pots	Loss of efficiency, high power input, red plates.	Control AlF3% to less than 11%. Reduce additions. Diagnose high ΔT from T trend.	Reduce AlF3 additions over two weeks and gradually reheat pots to 960–965°C without overheating.
	Bad airburn	Red carbon in pots, Exposed thimbles >10% of anodes	Airburnt anodes cause loss of cd and ACD.	Severe instability, low ACD and low efficiency.	Review cover dressing practices, and anode cover material.	As for early detection. Control anode unscheduled changes, dressing.

(*Continued*)

TABLE 5.1 (*Continued*)

Common Process Disturbances, Signs, and Responses in Smelting Potlines

Issue/ Mechanism	Possible Causes	Earliest Signs	Triggers—Stop Now	Consequences of Loss of Control	Response to Avoid the Event	Response (Damage Limitation)
Low Superheat (*6°C or less*)	High metal height, or shifts to higher metal	Low bath, hard crust at anode set. Swings in T/AlF3%, high alumina feed (cusum)	Not holding bath level, despite additions. Anode 'bath' spikes or deforms	High instability and power input, with pots at high superheat	Detect T/AlF3% abnormality, increase power, reduce metal level.	Reduce alumina feed and increase voltage target intil stability returns.
	Low V/I versus Qdissip	Same as for low metal level.	More spikes – but ACD related	Continual cycling of T/AlF3% and instability	Review heat balance formally–heat dissipation measurements	Same response as for early detection. Consider amperage increase
	Poor cell cover	High duct temp's, airburnt anodes-red carbon	Greater than 20% of anodes with stubs exposed.	Very high airburn, with low ACD and then low efficiency.	Review and correct anode cover practices and materials	Same response.
Anode Cracking	Anode CTE	Baked anode core property variation – cracks/ broken cores (baked cracks), CTE	Anodes cracking in pots with normal superheat 5–15°C.	Serious loss of pot, Potroom control: Rapid rise in high temp pots, anode noise, dust and spikes. Tapouts and many pots out of circuit.	Investigate any anode cracked – superheat, anode positioning, or anode quality. Track back to baked anode properties. Learn the signs – CTE, baking curves, core defects.	Track # anodes cracked in each pot, daily and respond. Extra PTM's pacmanning, extra PTM maintenance crews on shift. Anode inspection and crack detection before and after setting.

	High Superheat	See above for Superheat and	also for Anode	Cracking investigation.	Identify and treat high superheat pots early. Do not add excessive AlF3 amounts. Limit both alumina feeding and power input.	Remove sick pots (>1030°C) from circuit if PTM resources cannot treat other pots adequately (save the living). Clean up and restart sick pots.
Anode Cover	Operation practices	Large holes, over-covering, red carbon untended.	Greater than 20% anodes with stubs exposed.	High Fe%, poor cd in anodes, low ACD, voltage noise increased, variability in T/AlF3% and low CE.	Monitor cover practice – red carbon, holes. Keep % anodes with exposed stubs <10% in RR weekly audit.	Anode dressing standard and system implementation. Do not apply extra cover material or alumina to pots. Extinguish red carbon only.
	XS AlF3% in crushed bath	XS AlF3% >15% in bath phase	Bath gen. from cover gets too high – leading to alumina blend up.	Bad anode airburn and dust generation. Rod repair costs escalate and 'hard bath' at butt cleaning.	Tapped bath recycle and each shift recipe control into bath processing system. Monitor XS AlF3% in crushed bath.	Look at all methods of removing AlF3 mass input from the potline/bath processing system. No increase in alumina to blend.
	Alumina% blended	% blended >30%	See above	See above	Slowly reduce blend to less than 25% alumina.	Improve practices and reduce AlF3% of cover.

(*Continued*)

TABLE 5.1 (*Continued*)

Common Process Disturbances, Signs, and Responses in Smelting Potlines

Issue/ Mechanism	Possible Causes	Earliest Signs	Triggers—Stop Now	Consequences of Loss of Control	Response to Avoid the Event	Response (Damage Limitation)
	PSD	% −200μm >40%	Cover not controllable in level or bath gen.	See above	Work to reduce mill fines, and slugs of recycled fines. Monitor and respond on shift.	Get practices and tapped bath recycle under control first, then alumina blend and composition, then PSD.
Feeding problems	Feeder holes or feeder mainten.	Successful searches per day reduced, shots variable. Anode effect frequency.	Alumina cusum slope up. Noise increasing.	Pots full of sludge, low shots, high T/ low AlF3 and high noise plus low CE for weeks.	Work practices for feeder monitoring – open feed holes. Successful searches high.	Reduce feeding and frequent controlled searches/purge tracks. Control T/AlF3 and maintain ACD. Metal height.
	Alumina quality	Density down, shots up, spills/ piles	AE freq. too high, Cusum up.	Many pots full of sludge. Very high Noise.	Detect density or alumina fines >15% in pre-shipment samples, then adjust feed system to reduce overfeeding.	Lean out individual pots, run lower AlF3 (~8–9% or 1.2 CR until the sludge is working back into pot. Do not over-react with AlF3 add.

	Dense phase conveying system	Long or very short convey times (not enough, or overflow of alumina)	Spillage of alumina in pots, and/or fines in pot feed >25% Shots up.	As above, but on a geographical basis within the line, based on conveying system or GTC pot groups.	Condition based maintenance of the conveying system, including pressure pots, pipe scaling/cleaning.	Cleaning campaigns group by group, ensuring conveying velocities are reduced to dense phase range in all systems.
Cathode condition	Feeding control	Alumina cusum slope change up, sludge in tap/feed holes	Individual pots losing V stability and T control for long periods	Permanent deterioration in CVD and noise, higher power input and temperature, low CE.	Action on mechanical integrity of feeding on each pot – based on feed patterns, abnormalities. Include break/feed sequences	Replace bad breakers, adjust feed settings to run leaner, lower AlF3% target, higher metal height target and voltage target. Run with more tracking after operations.
	Covering practice	Pure alumina in channels, Fine cover blocking feeders	See above – but happens for pots in the same operating section.	See above – cathode deteriorates permanently	Remove poor cover practices – especially use of alumina to cover, and excessive cover instead of dressing existing material.	See above for alumina quality and cathode condition. Must gradually remove cathode sludge and ridge – over about 2–3 months.

(*Continued*)

TABLE 5.1 (*Continued*)

Common Process Disturbances, Signs, and Responses in Smelting Potlines

Issue/ Mechanism	Possible Causes	Earliest Signs	Triggers—Stop Now	Consequences of Loss of Control	Response to Avoid the Event	Response (Damage Limitation)
	Cathode heat balance	High bottom shell T, Corner anode setting	Pots of one generation or design, cathode type go unstable or have anode problems.	Pot overheating and failure, one by one as stability and control of power input, anode conditions are lost.	Monitor CVD, CCD and bottom/ collector T's on new generation/type pots to pick early problems with cathodic or insulation failure.	Discontinue construction of these pots. Adjust target V, AlF3% and metal to minimize chance of poor current distribution. Pacman and set 1cm higher than normal.
	XS AlF3% in bath	Short underfeeds, high slopes, Tbath <940	High AE's, spikes, rapid changes in T, high noise and anode probs	Low CE and possible sidewall tapout. Short operating life due to cathode freeze/ thaw damage. High potline variation in T, AlF3% and line CE 95→92, 93% over time.	Maintain target CR or AlF3 in the 1.1 or 10–11% range. Continually reduce 'Gain' of T control wrt AlF3 additions. Strategy of constant additions with T as a sensor for ΔT, then heat balance response.	Compensate in short term with metal and voltage, but reduce AlF3% over 2–3 weeks until cathode CVD and CCD returns to normal. Then reduce ACD again and metal. Prevent AlF3 add. below 950°C.

Pot design	Sidewall	High Shell T in local area only, rather than across most of pot perimeter (high ΔT)	Red plates on young pots, Si in the metal of these pots.	New generation or design of pot may all have a 'fleet' sidewall problem. Use of excessive compressed air plus tapouts.	Monitor group of each new generation of pot design to pick up problems. Thermally model each design before acceptance using qualified experts.	Air movers or heat exchangers (with fans) for minimum air usage. Tune ledge profile using metal, cover and voltage, pot by pot. Remove air wherever possible after rebalancing.
	Perimeter joint	High individual collector bar T's Loss of voltage stability and difficult to stabilize again. Erosion at base of s/w.	Generation of bath on many pots with high collector or lower side wall T's.	Loss of voltage stability, metal purity, followed by large scale, unforeseen tapouts of these pots.	Monitor CCD and CVD, plus lower sidewall ledge position on cathode. Test any change to metal levels(down) on pot group first. Avoid large Δ's in tap (>400 kg) or shifts in metal level >1cm.	Rapid increase in metal level of 4cm or more, with balancing 50–100 mV increase in Vtarget. Reduce cover to strengthen upper ledge. Maintain AlF3% <12% to avoid hard ridge and instability.

(*Continued*)

TABLE 5.1 (*Continued*)

Common Process Disturbances, Signs, and Responses in Smelting Potlines

Issue/ Mechanism	Possible Causes	Earliest Signs	Triggers—Stop Now	Consequences of Loss of Control	Response to Avoid the Event	Response (Damage Limitation)
	Cathode	Collector bar cd variation along pot extreme, High CVD not reversible, Fe% >0.2	High Fe on more than five pots, not coming down. CCD's affecting pot stability	Multiple tapouts and/or a fleet problem with the new type of pot/ cathode.	As above for sidewall design, and for cathode heat balance. Thermo-electric modeling before acceptance to detect faults in thermal, mechanical design	Cease constructing this design. Schedule damaged cathode pots out of circuit. Run remaining damaged pots at low superheat and higher metal, but lower CE.
	Overall heat balance – thermally deficient pot design.	High variability in T, AlF3% and bath height – poor thermal stability. Metal noise, bottom shell T both increase.	Large group of these pots (20) are thermally unstable.	A whole generation of pots with poor thermal stability and low CE, high power usage. Possibly low potline also.	Monitor thermal stability of new pot generation and tune the first ten pots over three months before building more. Assess target metal, cover, bath heights, plus voltage. Measure and close heat balance and compare with thermal predictions.	If across whole potline, consider slow amperage increase—based on constraints like anode condition, airburn etc., or bus bar temperatures. Consider also reduced metal height through better tapping and level control, cover level and material, AlF3% in bath (10–11%) and target V.

Rob was late for his daily update meeting with the general manager. It was two weeks since the potlines had gone into the "death spiral" as it had become known around the plant. Old hands just looked at him and smiled: "This is nothing, Rob. You should've seen it in the old days, mate. Back then we knew how to party."

They meant well, maybe. However, it didn't work at all. So far the damage was, as Rob saw it:

- Eight early pot failures in the last two weeks—between 800 and 1,500 days.
- Another six pots high in Fe now. May be able to cut them out, but at a loss of more pot days. Six pots out of circuit on average the last two weeks.
- Sixty anodes per day extra—that was almost 12% unscheduled change rate compared with less than 1% normally.
- Rod repairs 1,000 rods behind—stub damage and transition joints.
- Trending down now to only 10% of pots above 980°C. It had been up above 15% and stubbornly hard to bring down.
- Emissions limits on the potroom roof were blown for last month and this month already. Those consequences were now with the environmental group, but required reports back to the EPA (Environmental Protection Agency) and follow up monthly by Rob with them. Plus, a recorded EPA interview with Rob in case of prosecution.
- Two serious burns during anode burnoff removals—there was no good system for removing really large burnt off blocks from a pot. You had to resort to the manual burnoff pullers on a sling with the general purpose bridge crane (GP).
- Current efficiency was down to 86% this month. Last month's good result was only a memory.

Altogether a financial impact of between $7 and $10 million by the end of this week.

But, it was really the intangibles: people hurt, reputations lost. The (short leash) daily update for the general manager, the unanswered questions, no doubt soon the search for the guilty.

But, one question burned even worse than these matters. The general manager hadn't asked it, yet. What was the next thing that could happen on the potlines? And, the next one after that?

Opening the door to the management building, Rob remembered something one of the guys on crew 4 had said to him: "Don't go over to bullshit castle unless you need some of their product, mate." It made him smile on the inside.

Exercises

1. What do 5Ms and 1E stand for, in the context of diagnosing variation?
2. What are some early signs of a low bath superheat on a potline? What might be triggers for action based on this mechanism?
3. What would you expect to see in terms of feed data if the feeders or feeder holes are not being maintained correctly?

Keith Sinclair's "Understanding Variation" Flipchart

From Keith Sinclair, president of Sinclair Associates, Knoxville, Tennessee. With permission and grateful thanks.

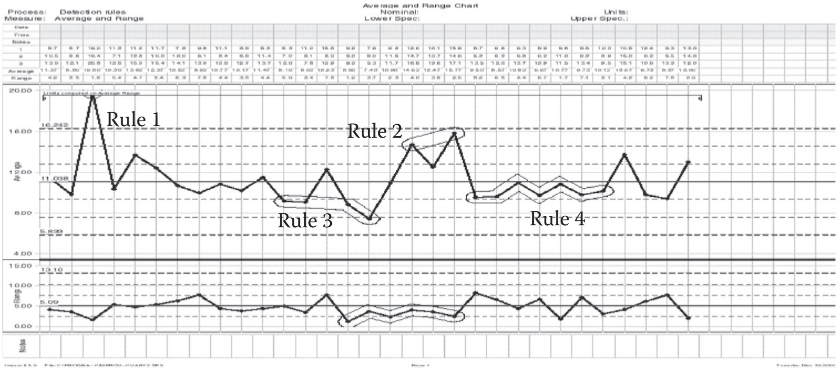
Rule 1: One data point outside three standard deviations

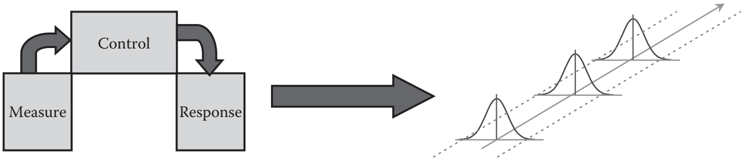
Rule 2: Two data points out of three outside two standard deviations

Rule 3: Four data points out of five outside one standard deviation

Rule 4: Seven consequential data points on one side of the mean

Understanding Variation





Statistical Thinking

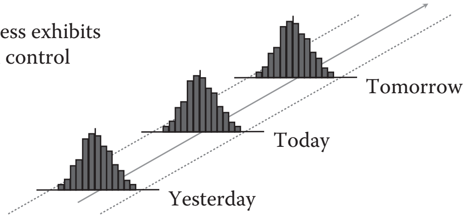
- Work is a series of interconnected processes
- Variation exists in all processes
- Understanding and reducing variation are keys to successful process improvement
- Decisions are based on proper data collection, analysis, and interpretation
- Actions on the process reflect our understanding of the process

Variation

- Variation exists in *all* processes – therefore, all data generated by process exhibit variation
- Sometimes processes exhibit variation that is stable and predictable (referred to as *controlled* or **common cause**)
- Sometimes the variation is random and unpredictable (referred to as *uncontrolled* or **special or assignable cause**)

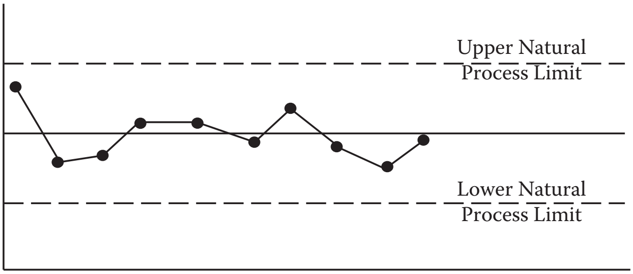
Controlled Variation

- Characterized by a stable and reasonably predictable pattern of variation over time
- Only common causes of variation are present
- This process exhibits statistical control



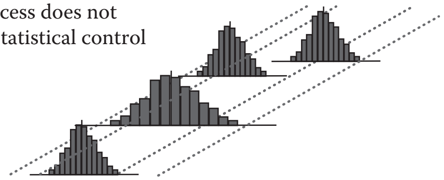
Controlled Variation

- On a control chart, it might look something like this



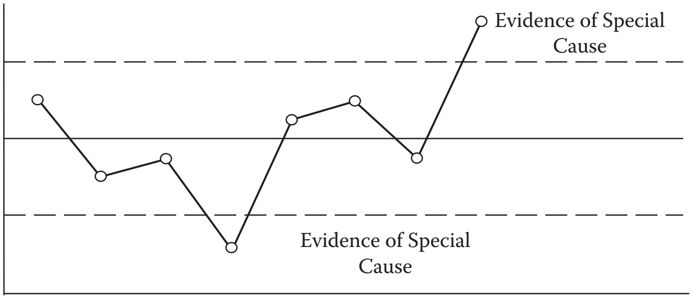
Uncontrolled Variation

- Characterized by a pattern of variation that changes resulting in an unpredictable pattern over time
- Special (assignable) and common causes of variation are present
- This process does not exhibit statistical control



Uncontrolled Variation

On a control chart, it might look something like this

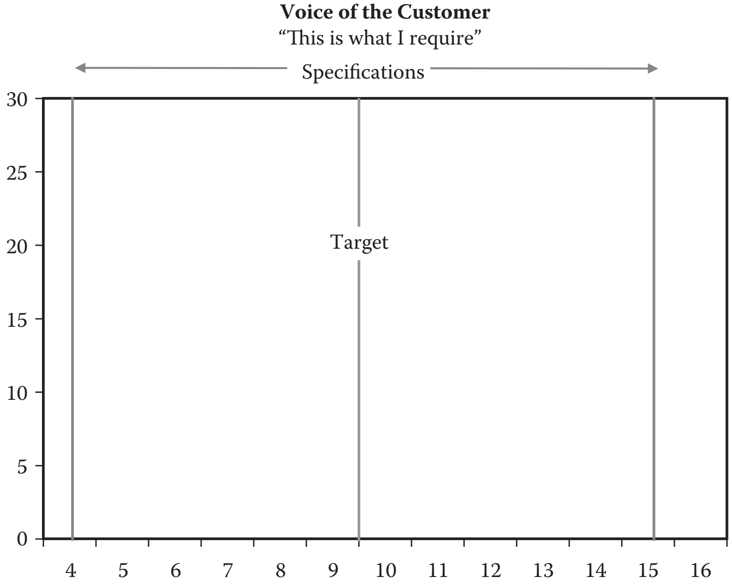


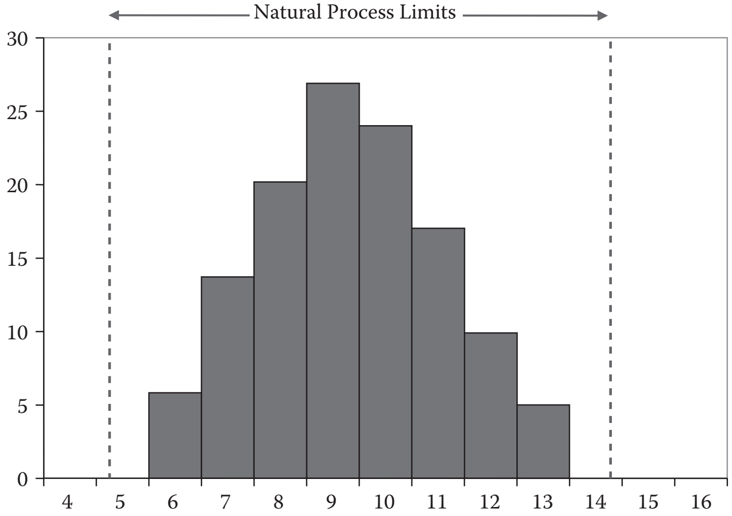
What is "in control?"

- A process will be regarded as being "in control" when, through the use of past experience, we can *predict*, at least within limitts, how the process will behave in the future.
- It is important that our processes are "In control".
- However, a process may be stable but still not meet customer requirments.
  e.g. a casting process that consistently produces 50% scrap.

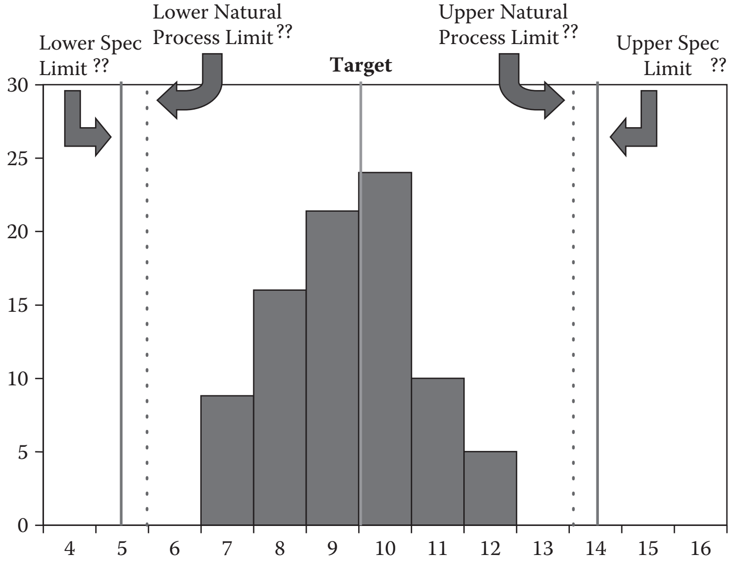
What is capability?

- A capable process is one that is stable and the measures always meet the customer's requirements (i.e. within the specification limits)
- The simplest way to compare the capability of a stable process to specifications is to draw a histogram
- It is a way of measuring how well the process meets the requirements. How well is the Voice of the Process "aligned" with the Voice of the Customer.

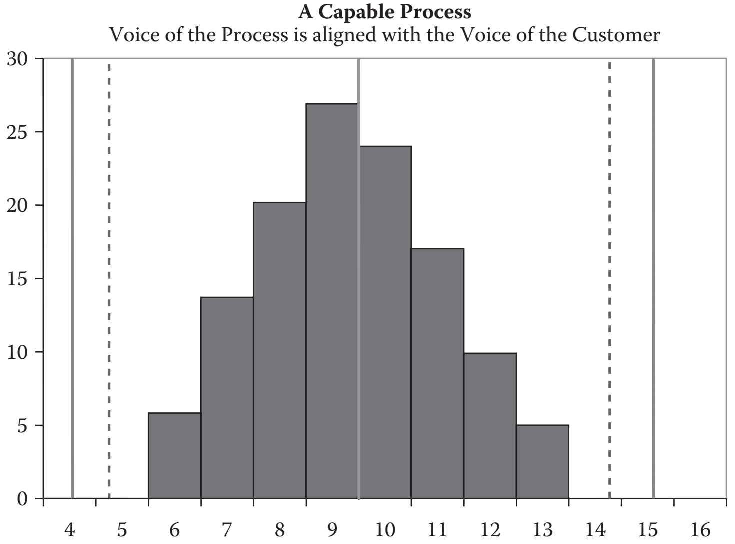


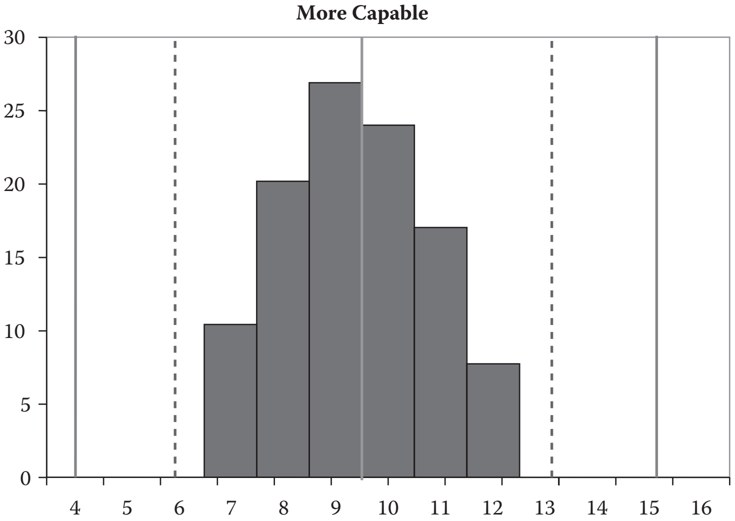


Voice of the Process
"This is what I can do!"



A capable process is one that is stable and the outcomes meet the customer's requirements (i.e. within the specification limits)





Questions to Ask When Assessing a Process

- Who will use these data?
- If something happens in your process, will it show up in these charts? How?
- What type of variation is the person interested in, and what decision might be made?

  - Variation types: within process, over shifts, days, weeks and hours? Within your process cf between subprocess—cells, reactors).
  - Is it common cause or special cause?
    - Between parts of the process: reactors, cell groups, sample subgroups, aggregated?
    - Both shift to shift and between parts of process or product?
- What sampling strategy is used, and what is the measurement variation (common) compared to the total range?
- Is there process event or control change information that is needed to interpret the variation in the chart? For example, start-ups, shutdowns, plant breakdowns/creep/other changes.
- What examples of variation here (on chart) might be associated with direct loss in value to the business? Why?
- How big a driver of plant performance is this measure? Is it a root cause, or a "knock-on"?
- What is the impact upstream/downstream of the variation? (Indirect loss of value.)
- How is the day–to-day (or shift-to-shift) variation estimated—range either MR2 or R of the subgroup?
- Is the range chart giving a proper estimate of the expected longer term variation in the Xi or X^- chart? Why not? (Wrong range or out of control?)
- What do *you* predict the variation will be in the next six months? Why? (Within control limits or not?)
- What is the control system or response plan that is authorized to act on this measure? What are the criteria for action? (Spec limits, auto control, no response at all?) Who will respond to the measure?
- What category of cause would you work on in this process? Only one?

Questions to Ask When Investigating an Out-of-Control Process

☐ Yes ☐ No • Are there differences in the measurement accuracy of instruments/methods used?
☐ Yes ☐ No • Are there differences in the methods used by different operators?
☐ Yes ☐ No • Is the process affected by the environment, e.g., temperature, humidity?
☐ Yes ☐ No • Has there been a significant change in the environment?
☐ Yes ☐ No • Is the process affected by predictable conditions, e.g., tool wear?
☐ Yes ☐ No • Were any untrained personnel involved in the process at the time?
☐ Yes ☐ No • Has there been a change in the source for input to the process, e.g., raw materials, information?
☐ Yes ☐ No • Is the process affected by employee fatigue?

☐ Yes	☐ No	• Has there been a change in policies or procedures, e.g., maintenance procedures?
☐ Yes	☐ No	• Is the process adjusted frequently?
☐ Yes	☐ No	• Did the samples come from different parts of the process? Shifts? Individuals?
☐ Yes	☐ No	• Are employees afraid to report “bad news”?

Note: A team should address each “yes” answer as a potential source of a special cause.

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6

Diagnosing Variation in Materials Processing

"I've looked at the past 12 months of potline data, Rob," said Tony, the statistician whom Rob had called for help. "There's a lot there, and I can't interpret why many things have happened. That's for you. However, I can say that there have been 10 instances where the process has gone into an out-of-control state for a period of a week or more: either temperature, AlF3%, pot voltage, noise (mV), AE (anode effect) frequency (AEF), anode problems, unscheduled anode changes (USCs), Fe%, Si%, or some combination of these."

"Okay, but things happen in production, Tony," Rob said. "We have to roll with the punches, so those instances get the appropriate response and we don't lose control of the plant."

Rob and Tony were alone for a half-day session that Tony had insisted was not a "one-hour summary."

"I haven't explained those 10 events yet, Rob. Eight of the instances of loss of control were not actually identified at the time they occurred. So, there was no chance for anyone to diagnose or respond to them. All you can do is clean things up afterwards, just like you had to do with the loss of superheat control that led to anode cracking and spiking. At least that loss of control was properly documented, I suspect because you investigated it yourself."

"And, that was because it was so serious it brought the smelter to its knees, Tony," Rob remarked. "I don't need any more experiences of that type, thanks." Tony had Rob's attention now.

"Yes, but that is just the problem right there," Tony said. "The other seven occurrences of loss of control didn't result in critical plant losses, but that was just a matter of chance. You never knew about them, and so you would have been in the same situation, which was reacting when a large proportion of pots were already in poor condition, and cleaning up the mess afterwards."

No, I wouldn't, Rob thought. One more event like the last one and I will be looking for "new career opportunities." "Okay, Tony. So, your point is that we need to put in place some better data systems, right?" Rob was looking to cut to the chase. He needed a quick fix.

Tony shook his head. "Not that simple, Rob. You do need some better presentation of data, no question. But, it goes deeper. You haven't asked about the other two loss of control events. Your potroom exceptions system on the Level 2 did detect those ones."

"Then we got them before they caused us problems. That's the response we're looking for, isn't it." Rob didn't mean it as a question.

Tony was quiet. He had something else to say. That was one of the things Rob liked about him. He was no cheerleader. The silence began to penetrate Rob's thick production skin. "Okay, tell me, Tony."

"Well, the responses in both instances were to get the pot controllers on shift working all their time getting these exception pots back in condition, one by one, Rob. That might have been needed. But nobody looked at why 20 to 30% of pots went out of their operating windows within a few days of each other and created those exception pots in the first place.

"No attempt was made to diagnose the cause of either event. So, my conclusion is that these loss of control events will keep happening until you get one by chance that overwhelms your resources again or just isn't picked up until way too late."

Tony was speaking so quietly Rob had trouble hearing him.

"Okay." Rob leant back in his seat and looked at the analysis. Tony was explaining each event, all 10 of them. He had replotted the variables so that you could look at all the pots together quickly: 20 to 30 small trend plots on a page, to pick visually any pot behaving strangely. Then, in a second format, the mean and standard deviation of each potline or section, for each variable, along with the distribution of the pot section over time in box whisker form, and the distribution of each pot along the section over the same period. The detailed distribution of pots at the end of the period also was there on the same one page, "four plot."

These four plot charts interested Rob most at the moment. You could look at the entire potline or potroom on one variable, and get different views simultaneously. And, it signaled statistically, so you could see not only if and when something had changed but also where geographically (which pots or section of pots) things had started to behave differently. However, then the reality of what Tony had said just a few minutes earlier began to hit home.

"Tony, what you are talking about are the events and the charts themselves, and I'm glad you got inside them enough to do that and plot the data this way. But, I'm looking for what I need to do about this as production manager.

"I can't be around the plant looking for problems every day. When it started to turn to crap last time, I was out of the plant on an Industrial Accidents course. Then, I had a management workshop for two weeks after that. I need the production team to get all these process signals, diagnose the causes, and remove them. But, you're telling me that isn't happening and that new graphs won't fix it. What is the problem here? Don't the guys know how to run the plant? They've been doing it since Adam was a boy."

A note of frustration, or maybe desperation, had crept into Rob's voice.

Tony was quiet again but focused on the charts. Rob realized he had gone a bit too far.

"You've given me a lot to think about today, Tony. I asked you to give it to me, and you gave me both barrels. Thank you for getting to the guts of it for me. Can we get together later tomorrow and go through the next steps? I really need to think about this before we go on."

Tony looked more cheerful. "No problem, Rob. I'll be here whenever you want to reconvene."

A Production Manager's Analysis of the Plant's Control Systems

The diagnosis of specific variation patterns is not occurring in the production plant above, probably because it is difficult, time consuming work that uses production resources and has no immediate or certain outcome. One of the consequences of this lack of diagnosis is that the production process accumulates more and more undiagnosed causes of variation, such as causes of large temperature/composition shifts, latent failures or errors embedded in the potline automation systems, and pots with special cathode or superstructure-related problems. Over time, the level of "common cause" or base-level variation then will gradually rise and obscure important signals that the process is being disturbed. Individual causes cease to be identifiable as special cause variation under these circumstances. Cause analysis in these situations is much more difficult due to the absence of a single "special cause" signal in the data.

This finding reinforces the need in modern production for online "process analytics," which give rapid analysis of variation and clear signals for action, for which standardized responses can be developed with confidence because the cause is known. These more advanced diagnosis techniques will be discussed in chapter 12.

However, the lack of recognition or attention to the obvious signals in the process data is a more serious problem in the present situation. This is a common problem observed in production plants. There may already be charts in the plant that clearly show the variation and signals of process abnormality (as in the potline situation here). But these signals do not appear to have been recognized, and there are no associated analyses or control responses until the process moves into an unacceptable operating region or quality of the product itself is badly affected. By this time, the process abnormality has turned into a full-blown crisis (large proportion of pots affected), and the damage to production and the product is well advanced.

The diagnosis of variation in production is exacerbated because the control loops are typically univariate and compensatory rather than being based on analysis of the causes of variability. For example, in potlines, most of the process variables are strongly coupled through the heat balance and mass/energy control/manipulated variables. Bath temperature and cryolite ratio move together, often in response to thermal drivers, such as voltage instability, metal height, bath height, anode problems, but further magnified by AlF3 additions or target voltage changes. Complex thermal and alumina feeding dynamics follow, along the lines of the thermal and materials balance principles discussed in chapter 5. A steady heat balance in turn is highly interdependent with the electrical and electrochemical smelting mechanism that underpins the success of the whole process—*uninterrupted, evenly distributed, and mainly vertical current flow from the anodes through the molten bath and metal layers into the cathode assembly.* This two-way interaction between heat balance and current distribution is the core of the smelting problem, and if the heat balance is continually perturbed by abnormalities and control reactions to them, the current distribution is also perturbed.

As still taught in some control courses, univariate pot control loops are manipulating designated control variables to compensate for each of the process variables, usually in some proportional way relative to the deviation from target. This very often contributes to and hastens a process excursion. The triggering event for identification of a potline process excursion is likely to be a significant increase in temperature on a large number of pots in some parts of the potline (as in the present case). These temperature increases could be associated with target voltage increases by section operators, prompted by voltage instability in their sections. However, the causes of the voltage instability were actually anode setting issues, for example, possibly connected with new staff or poor control of anode setting procedures. These causes are obscured when the initial instability signal is countered by the extra voltage because the problem has been "dealt with."

Unfortunately, a separate control loop is simultaneously responding to the increase in temperature; the bath composition control system on the potline responds with higher AlF3 additions rates, because this is the main manipulated variable for bath temperature control. The high AlF3 addition rate increases the AlF3 content in the bath and can actually increase the voltage instability on many pots, causing even more voltage additions to be made by the automatic system, because anode cathode distance is the main manipulated variable for reducing voltage instability. A diagram showing the interaction in the basal pot control loops is given in Figure 6.1:

Continuing reinforcement of the extra voltage additions increases temperature again, giving rise to further AlF3 additions and resulting in a higher AlF3% in the bath and more instability. Higher superheat- and cathode-related instability due to alumina feeding disturbances are now affecting a proportion of pots, and this can give rise to a dangerous situation.

If special cause anode quality variation is also present at this time, for example, a batch of higher density coke with a higher coefficient of thermal expansion, there is a strong probability of anode failure on a proportion of pots as shown in Figure 6.2.

In fact, anode corner cracking and end cracking occurred across many of the pots on the potline in the case described above, leading to a large

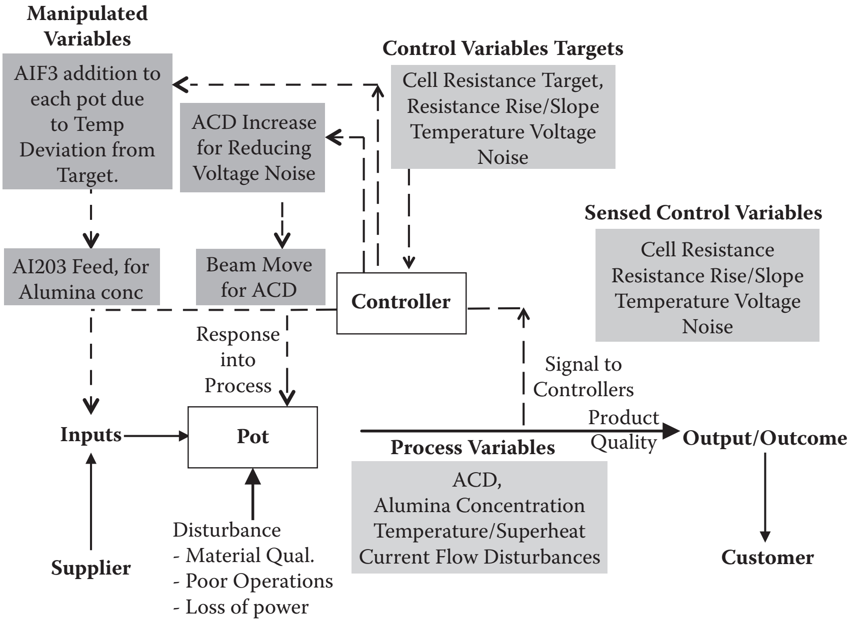


FIGURE 6.1 (See color insert.)
Basal automated control loops and process variables for a smelting pot.

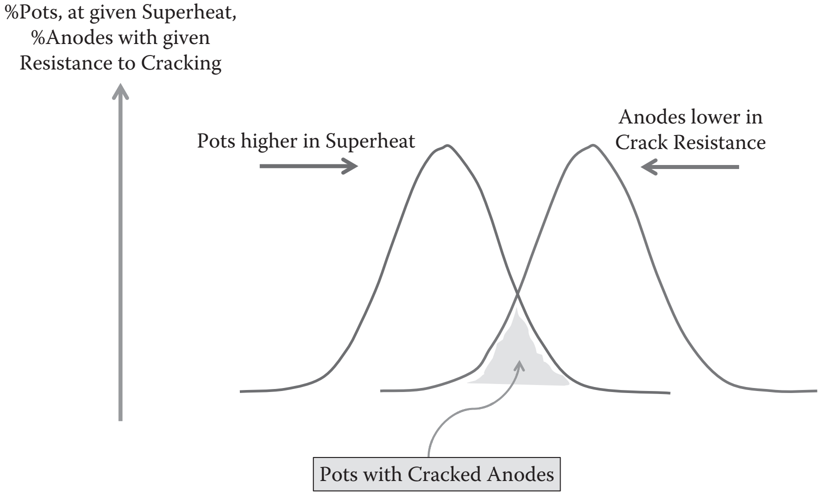


FIGURE 6.2 (See color insert.)
Effect of variation in potline superheat and anode cracking resistance. (Courtesy of Barry Sadler, who crafted the illustration one day on a whiteboard.)

number of sick pots. The extra attention needed by section operators or pot controllers to tend sick pots has a negative influence on the other pots, with a general reduction in current efficiency, plus attendant loss of control of carbon and energy usage, and sometimes safety.

The analysis with respect to the above situation, therefore, is focused on three issues:

1. *The failure of the basal automated control loops*: The change in the sensed variable (for example voltage instability or noise) is not actually diagnosed in terms of its cause. Rather, the use of a comparator against a target value or limit for this variable, and the automated connection to a manipulated variable (extra voltage) leads to a more serious disturbance to the process condition. There is no identification of whether or not the variation in the sensed variable was within natural limits or had statistically changed. The chance to improve the process by removing the bad anode setting practices also is lost and the problem, therefore, will reoccur at a later time.
2. *The failures in control of practices* (anode setting and voltage increases) that allowed voltage increases to be accepted as an authorized means of solving the problem rather than finding the reason for the instability. This is the behavior that originally tipped the fragile automatic control loops out of their stable oscillation zone.
3. *The failures in overall process management* in the potlines that should have identified the special (statistically abnormal) variations in noise and in temperature/AlF_3 additions, and diagnosed them at an early stage, long before anode cracking eventuated.

Later that night, Rob dialed an international number. He hadn't talked to Paul Mahon for some months, but he needed the counsel of a more experienced production manager. And, Paul had very high standards—right from when he had been an operator. In fact, maybe that had a bit to do with it, Rob thought. Paul knew every task in a potline intimately, including being able to read the signs of a problem—and then fix it.

"Yeah, I see where you're coming from, Rob," Paul remarked. "It's that old question:'What's the problem here'?" Paul gave his trademark chuckle. Strangely reassuring.

Rob had loaded up on Paul, and given him the same question he had just raised with Tony.

"I think the thing that is different for the plant now, compared with in the past, is your own expectations, Rob," Paul replied to him. "The way you want it to run and to be run. Some production managers are happy when "shit happens" because they have something to do, and they usually find someone else to blame for the original problem. The carbon plant is always good for laying off some blame, or the casthouse sometimes, or the alumina, or even the supply guys because of the cathodes they ordered. Production managers aren't usually big on analysis or diagnosis. They are fast on their feet. And, their production teams are used to reacting hard and fast to problems. By the time they hear about them, they're usually big problems. Just like your statistician said. But, now you have the expectation that the production team will immediately start using a scientific method because some new charts are on the computer? You want them to sit down and diagnose problems before they even show up as damage to the process? That won't come naturally, if it comes at all.

"I reckon you got to see it as part of a new production culture, Rob. It might need a change in organization structure as well as in the control system. It's measuring your production superintendents on different things as well. The management system has to line up with your new control expectations. Providing fancy new computer tools and waiting for it to 'just happen' might be an even better definition of insanity than the one we used to have."

As usual with Paul, a joke softened the incisive logic.

At 7 a.m. next morning, Rob drove down the straight with purpose. He had the bones of a plan. But, what he needed first was to understand the method Tony was talking about in more depth. It was very soothing to talk about the "scientific method" as you demonstrated it in retrospect to things that had already happened, but another thing to actually test it in real time—to predict things that were not known.

"Tony, is there any way we can give this databased method a road test, even if the process is not actually going to hell in a hand basket right now?" They were seated at the conference table, and Ford had joined them to get his "fix of statistics," as he said with a smile.

"Great idea, Rob." Tony pulled his laptop around so they could see it.

"As luck would have it, the 10 out-of-control events this year might be being joined by number. 11 right now."

"Real poor turn of phrase, Tony. But please go on." Rob and Ford watched as the screen told the story.

A Nascent Process Disturbance Diagnosed Using the Scientific Method

First observations of a problem, such as airburn, are visual, as below. In this case, the airburn is beginning just above bath surface on the anodes (Figure 6.3), spreading to the corners where the radiant heat transfer between anodes is highest, and then burning inwards and upwards toward the stub holes, as shown in Figure 6.4.

The key lagging indicator of the problem is one or both of the following:

- High unscheduled anode changes (USC) as a result of airburn. Shift crews will often remove anodes that have been airburnt to the extent that cast iron thimbles of one or more stubs are exposed; and

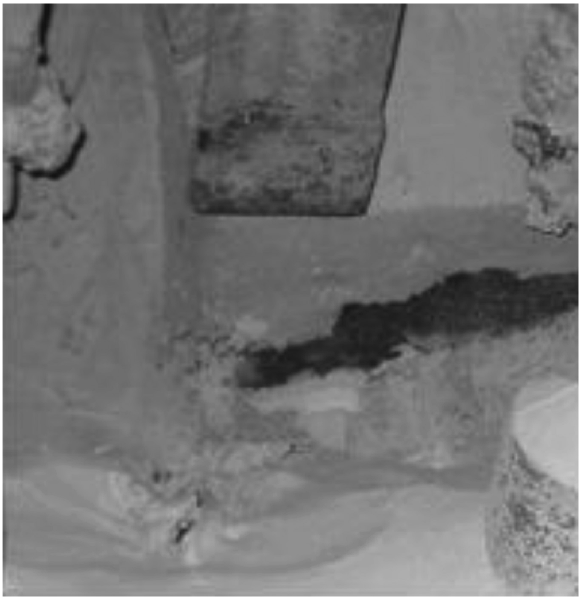


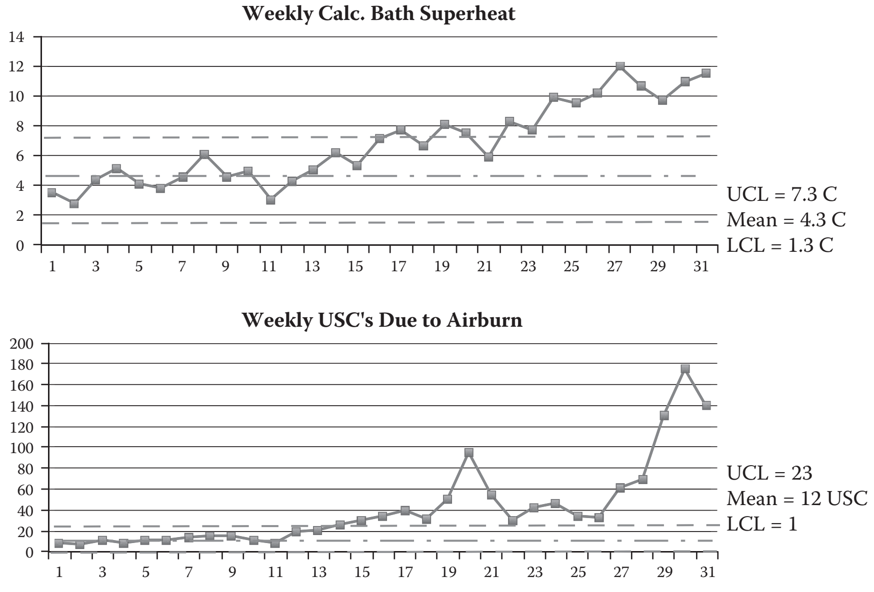
FIGURE 6.3 (See color insert.)
The start of anode airburn near the bath surface and on the corner of the anode near its slot with the adjacent anode.

FIGURE 6.4
The eventual outcome of the airburn process when the carbon has been burned back to the anode stubs, reducing the length of this anode by about 15% in only a few days and exposing the cast iron of the thimbles around the stubs.

- High iron concentration in the metal, as a result of direct bath attack on the exposed cast iron thimbles and stubs of airburned anodes. This is an indicator that the airburn is more advanced and constitutes greater process damage and economic loss since the aluminum purity, the anodes, and the anode rods themselves are degraded.

In the present case, the potline crews are removing the anodes proactively to avoid the secondary damage to the product. The number of unscheduled changes in any shift, therefore, represents the view of that particular crew about how many and which anodes are in danger of sustaining extreme airburn damage.

Weekly totals of USCs for a period of 31 weeks are shown in Figure 6.5 for one potline, along with the calculated bath superheat on this line. The detection of an airburn process abnormality can be made in this case at or slightly before the nineteenth week, on the basis of the individuals chart shown here, despite the fact that the removal of USCs is an inherently variable process because it is related to the workload of the crews and other factors. However, the magnitude of


Weekly Calc. Bath Superheat

Weekly USC's Due to Airburn

The Present Day at Southern AL

FIGURE 6.5
Weekly average calculated bath superheat, and the correlation with weekly unscheduled anode changes (USCs) due to anode airburn, in this case.

the weekly increase in USCs swiftly breaches the upper control limit and could possibly have been detected several weeks earlier, if it had been plotted at that time as an ImR Control Chart rather than a daily run chart.

The calculated bath superheat also has many sources of variation, including the AlF_3% sampling and chemical analysis variability that is no better than +/− 1% AlF_3 in repeatability, and the fact that the alumina concentration is assumed rather than assayed. The impact of this variability is reduced through the use of weekly potline superheat averages as individuals in the ImR chart here. This has the disadvantage that information about changes in the distribution of superheat across the potline is not considered—an X_bar – s.d. chart can achieve this if the pot-by-pot data are available. The latter chart, therefore, will signal earlier in many circumstances than an ImR chart of the potline averages.

Even with this disadvantage, the Average Weekly Superheat control chart is also signaling strongly by week 19.

If the airburn increase is actually detected at this time by the smelter staff, and if it is then diagnosed, the later consequences shown after week 25 can be avoided. In fact, the consequences in terms of process damage extend much farther into the future and more deeply into the economics of smelters than is shown here, as indicated in the Table 5.1 which contains a column detailing the consequences of loss of control for various common process disturbances (Chapter 5).

Immediately after detecting the problem at week 19, a number of operating variables should first be investigated because the most likely trigger mechanism is increased access to the anodes by air:

- Deterioration in anode cover, either quality of material or quality of dressing practice.
- Variation in liquid bath levels (or liquid bath transfers), which creates very hot vertical carbon surfaces for air to access.
- Anode current distribution (ACD) problems due to anode setting profile or accuracy or low ACD, causing high anode temperatures in the first few days after setting when vertical surfaces of the anodes often remain uncovered.

In addition to these variables, other heat balance factors also could be important:

- Duct gas flow rate, and heat off-take from the top of the pot
- Stub to carbon voltage drop and variability
- Actual bath temperature (as opposed to bath superheat), which can affect the temperature of the anode near the bath surface

The properties of the anodes and, in particular, their variability should be studied in parallel from baked anode core data:

- Differential reactivity of pitch due to baking temperature or composition (sodium content, for example, although this would also cause dust)
- Carbon resistivity variation
- Permeability and other properties

In fact, there are likely to be a number of factors involved in any case of airburn. This makes it especially difficult to use classical univariate SPC (statistical process control) to deduce the cause from an out-of-control signal and track down a single process change that corresponds to it. In fact, there may be multiple variables "signaling" in the proximity of the airburn initiation, and often they are throughout the smelter. A "needle in the haystack" situation can result.

This is why a more comprehensive use of the scientific method is needed in many production problems. A mechanistically based hypothesis for the cause, like *superheat initiation of airburn near the bath surface*, backed with data on the problem and elimination of more obvious factors is the correct path. This is the starting point for an hypothesis meriting further testing.

Thus, next it is important to question whether the airburn process has been initiated by the significant change in weekly superheat on the potline. Certainly the superheat trend seems to be coincident with the trend in airburn, from the above data.

Unfortunately, there is also the possibility that heat generation from the airburn process becomes self-sustaining and is increasing average bath superheat. To eliminate this as an alternative, the question then is*: Are there any clear drivers for the increase in average calculated bath superheat, which occurred significantly earlier than the outbreak of airburn?*

In Figure 6.6, the average heat balance on the potline is examined. Evidently, a gradual increase in metal level has occurred starting about two months ago, in weeks 9 through 10. In fact, this was due to a process change that increased the metal level targets.

The consequences of this change included increased noise level, although this apparently took time to develop fully. However, pot voltage was higher by 40mV through a combination of noisy voltage and operator voltage from weeks 12, indicating that the cathode condition and metal pad current distribution had probably been affected by the metal level change. Cathode ledge growth is the most likely mechanism for the increase in noise and in operator additional voltage.

The result of the increase in power input is an increase in average pot superheat and probably also an increase in top heat loss although this is not quantifiable without extra sensing of the duct gas temperature trend.

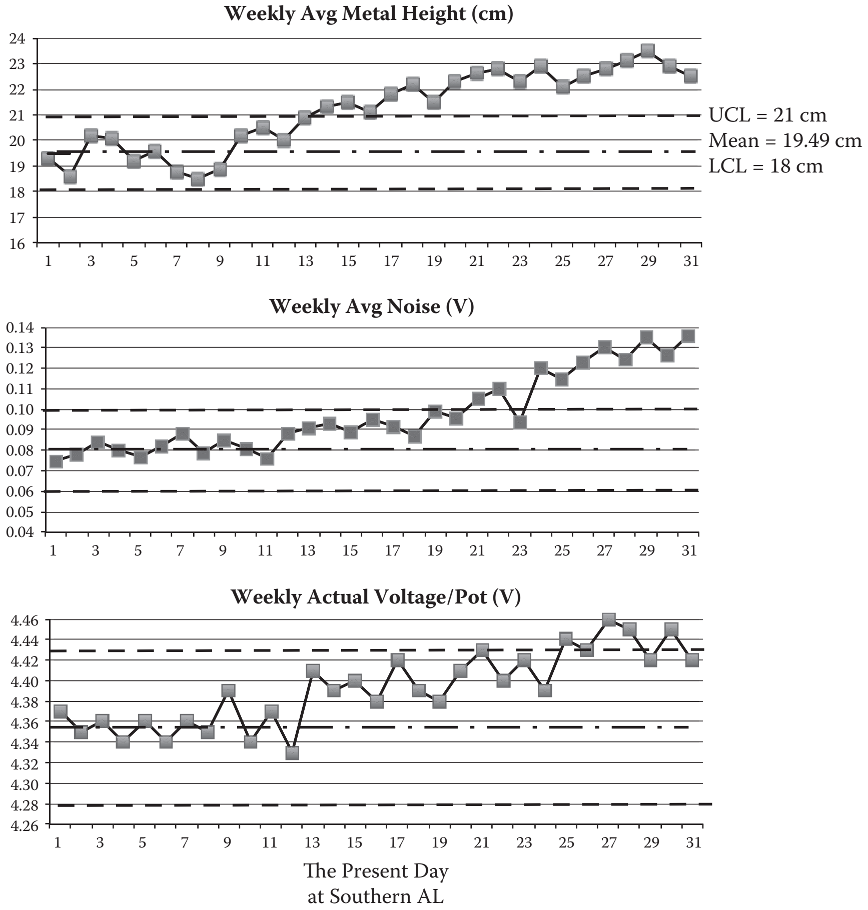


FIGURE 6.6
Average metal height, voltage noise, and total actual voltage, showing the causal effect of cathode heat balance and sludge deposits on noise and, therefore, actual voltage to the pots.

The increase in superheat from weeks 12 to 17 would not be significant at the 5% level, but is still useful in the construction of the hypothesis.

The above analysis has so far neglected the impact of variation across the potline. From an operational viewpoint, there are most often 10 to 20% of pots that are generating 60 to 80% of the problems, and this also may be true of these anode airburn problems. Unfortunately, such information is often not collected (i.e., which pots had how many USCs due to airburn on each shift).

Stratifying this variation (examining USCs by pot, by section, by crew, etc.) afterwards will certainly help to get to the root cause, e.g., by looking at which section of pots had the first or largest increase in superheat, or USC. However, a much better use of the information would be if the pots/sections with high USCs were identified during the same week they occurred and the precursors or drivers of their superheat investigated right then, when the information is still fresh in the minds of staff and before damage to the potline.

This is now known as the Lean approach to process improvement. But, the trail had already been blazed by Toyota production lines in the manufacturing industry—the *Andover cord* being one often quoted example. The difference in materials processing industries, such as aluminum production, is their complexity and low direct observability. The steps of *hypothesis and experiment* are sometimes unnecessary in manufacturing or assembly plants because most variables of state are measurable, and variable relationships tend to be more sequential and linear. This is not the case in materials processing, however, and correct execution of these two scientific steps is the difference between success and failure to improve.

There is now an evidence-based hypothesis for how the airburn situation developed in this particular case, based on a shift in heat balance due to noise, itself triggered by cathode freezing when the metal reserve was increased. With this step, many such airburn investigations have ended. The production manager may see this hypothesis as the probable cause, weigh up the risk of being wrong against the risk of "doing nothing," and then take action. That action might be to adjust a number of parameters on the entire potline simultaneously to reverse the heat balance trend as quickly as possible and also to cover his or her bets on the other possible airburn factors listed earlier.

This is an understandable human response in situations where delaying action can have large economic consequences. However, there is a serious flaw in its logic. The course of action assumes that:

- *The hypothesis concerning the cause is accurate and complete*, although this is seldom the case due to the number of unknowns bearing on the pot heat balance across any potline. Factors such as aging of the cathode population, changes in alumina quality and dissolution characteristics, and changing amperage can all change cathode condition and the background level of noise due to metal pad movement; and
- *The cause can be removed by removing the factors initially associated with its appearance*. But a shift in heat balance to a higher superheat due to poor cathode and/or metal pad current distribution always causes other problems over time, such as disturbed feed control and deteriorating cathode condition. Therefore, even an accurate cause analysis does not automatically translate to a solution to the problem, i.e., a removal of the cause.

In short, in materials processing and production, there is a much higher uncertainty about the pathway to solving complex problems. That is why so many of these problems, such as airburn, recur for years or even decades during a plant's history without being solved. Outbreaks of airburn have dogged many smelters for more than 20 years and hindered reduction of pot voltage, improvement in current efficiency, and, more insidiously, flexible operation with respect to amperage and production rate. An experiment is needed to positively (or negatively) test the hypothesis that has been formulated and with sufficient confidence that the result may be used into the future.

Therefore, the alternative, rational action for a production manager is to design an experiment to prove that the hypothesis is correct or needs modification. To do this, however, the hypothesis must be recast in a "testable" way:

> A reduction in average bath superheat to previous levels of 4 to 5°C (calculated) will reduce airburn to a level where USCs are reduced to previous low levels.

However, an economically viable time to test an operational hypothesis, such as this, is one month in a potline and not more. After this time, many things that affect the heat balance can change and, in all probability, make such experiments invalid or irrelevant. Using BACI experimental design,[1,2] this one-month experimental time frame is possible due to the removal of the dominant pot-to-pot variance component from the total experimental variance. However, even using BACI, 50 pot experimental and 50 pot control groups are required to achieve a significant response over this time, which is considerably more than the 10 to 20 "pot trials" that are common in the aluminum industry.

In BACI experimental design, the performance of these two 50-pot groups is examined with respect to primary response variables (USCs and bath superheat, in this case) both before and after the experimental treatment is applied, thereby allowing the individual pot characteristics before the experiment to be taken into account in the analysis, and this component of the overall experimental variance removed from the response to the experimental factors.

The next question is how to manipulate the complex heat balance of the pots to achieve a reduced average bath superheat in a sustainable way, in other words, in a way that can later be applied to the entire potline. Ideally, the cause of the increase in superheat should be addressed. This cause is the excess power input being provided by the higher pot voltages on the line. However, the higher average pot voltage is in part a response to the increased average noise, and this has built up over a period following the increase in metal levels.

This potline situation should be a salutary warning to production managers who allow metal levels to increase over time as a compensatory response to voltage noise or overheating. The effects on the cathode heat balance and buildup of surface deposits of corundum can be long lived or permanent. The same warning applies to using aluminum fluoride addition for the same purpose. Both of these process "crutches" inevitably degrade the cathode surface condition and eventually the internal structure of the cathode block through freeze/thaw damage over time.

A screening experiment on a small group of pots not in the test group is warranted to determine if and how the superheat on the 50 pot test group can be reduced without serious consequences. Further analysis of the additional average pot voltage in this case shows that half of the (40 mV) additional voltage used came from operator voltage additions rather than automatic noise voltage. The reason for this is that operator voltage often stays on the pots for longer and causes overheating as a result. Removing this operator voltage completely, along with a 1 cm metal level reduction, and a 10 mV reduction in nominal voltage is the type of small adjustment that may be successful in reducing the bath superheat over one to two weeks without increasing voltage noise unduly. Reduction of cathode ledge/ridge as metal levels reduce also should gradually reduce the voltage noise if the original hypothesis is correct. Note that the risk of anode spiking or poor anode current distribution needs to be guarded against in this screening experiment.

Given a positive trend in a 5-pot screening experiment, the above or a modified treatment would then be applied to the 50 pot test group. It is understood that test and control group's must be in the same operating area and not have other important differences, such as different alumina supply or crushed bath cover supply. One way to accomplish this in practice is to have odd and even numbered test and control groups in the same pot room, as practiced by Rutledge[2] in his potline experiments over the past 10 years.

The experiment itself should be analyzed each week to see if differences between the test and control group's weekly response variables are developing. Even with the delayed response of the test pots to their power input and metal level reduction, one month should still be sufficient to see differences emerging in the weekly average superheats and USCs of the two pot groups.

Rob looked at Ford. It hadn't made much of an impact. "But, how did that experiment turn out, Tony? Sure, we got problems, but we always get through them. I don't know that this method is really going to get us there faster."

"How it turns out depends on you really, Ford. You can take control of your own future here. That's really what the scientific method is about," Tony responded. He had laid out the probable result of not doing that, from his previous experience. It hadn't looked pretty by week 30, and Rob and Ford knew they had been there before.

"We do have problems, Ford. But, they seem to be the same problems. And, we keep getting a bloody nose from them. I guess you've noticed that, right? They're not getting solved, only lived with," Rob said. He decided this was a good time to let Ford in on the first part of his plan.

"We're going to have a separate team take responsibility for improvement in the process; for solving the hard, persistent problems that we have in production, and alerting us to when other problems might be on their way, Ford. You're production superintendent, and you're going to have a process superintendent to help you from now on."

"We haven't been allowed to recruit for about two years, Rob. Good luck with that," said Ford, who was correct in this observation.

"No, and that was a good thing, too. We have enough roles in the organization. But, we don't have the right roles. So, from next month on there won't be a dayshift crew leader role anymore or process control engineers reporting to each line. Those engineers and the crew leader will now report to the new process superintendent, and I will be appointing a person to that role in the next month," Rob remarked.

Rob turned to Tony. "That was exactly what we needed, Tony. I want you to work with the new process superintendent when we find the right person. And, Ford, you will be the main beneficiary of the new team's work, from day one. Guess what problem will be attacked first?"

No, answer, but a smile from Ford. He would be the biggest champion of the new method of running. However, this was only the first part of the plan.

Rob knew how hard it was going to be to bring the new culture to life. New information systems were a key driver of change, especially in production. He needed the IT department to get with the program. If data could be presented in the right way, then accountability for each key potroom variable could be assigned, and the teams represented in the smelter flowsheet he had drawn would be able to work on the responses needed for each variable.

The third part of the plan was new accountabilities for the leaders. With a new set of measures aligned to stability of their key process variables and outcomes, Rob could hold each superintendent accountable for losses in control and drive the new scientific method through the organization.

So, that was the plan. As he drove back along the dark road that night, Rob thought he could remember from his dull poetry lessons in school something from Robert Burns about the best laid plans of mice and men. What had happened to those plans? Poetry hadn't stuck with him, at least not enough of it.

Exercises

1. Refer to Figure 6.1 showing the basal control loops for a smelting pot. How many control loops are represented on this diagram? How many of these depend on only one sensed signal from the pot? What is this signal, and how is the separate information about it collected in a way to isolate its response to each of the process variables?

2. For these three control loops, what is the assumed cause that the controller is seeking to respond to in each case, in order to maintain the process variable on target? For two of the control loops, give three examples of other causes that may be present and that the controller should not respond to in this way.
3. In your opinion, and for discussion within your groups, what is the main reason for the lack of attention to the "out-of–control" signals by the staff of the potlines, as observed by the statistician and the production manager.
4. Read Chen and Taylor.[1] Describe the main difference in the BACI experimental method, and why it reduces the experimental variance.

References

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2. Rutledge, S. 2008. Statistical methods for use in the aluminium smelting industry. In *Light metals*, ed. D. H. DeYoung, (pp. 325–327). Warrendale, PA: TMS (The Minerals, Metals & Materials Society).

7

Understanding Potroom Processes

Rob looked again at the smelter flowsheet he had sketched in the course, which seemed a long time ago now. The flowsheet had the entire smelter on it, and that was good. But, because of that, it didn't identify what was really happening inside the potrooms. It looked like a black box. Rob smiled. Yes, that was how his boss described the potroom, a black box, full of things that would trip you up and run you over before you knew it.

Being inside the black box didn't feel so bad, actually. People there were self-reliant and cheerful, whatever was happening. But, that didn't help Rob much because what was happening wasn't good. Where was the chart that identified all the potroom processes and what people were supposed to be doing to control them?

"Ha, yeah, that's a good one, Rob. You keep thinking about that. We'll just go and tap some metal, okay?" There was a mischievous smile on Barry's face as he turned and started walking down line 1.

Shouldn't even have asked him the question, Rob thought, as he made his way through to center passage.

Back in his office, Rob started to sketch out inputs and outputs from the black box that was the potroom. Then, he looked at where these inputs and outputs were coming from. Actually, for every input/output combination, in the middle somewhere, there was a process with someone or something (like a computer) controlling it.

The diagram started to get complicated, and Rob ran out of whiteboard.

"Steve! Come in here."

Steve Harris was the new process control superintendent, and it was his third day at the plant.

"It's time you got those new boots worn in, Steve. I want you to work with all the crews on making a diagram like this one that describes the potroom processes and the work the guys do to operate them, first, at a high level like in this chart, and then get into the detail of what the work practices and control procedures are as well. I want a management system for our processes."

In two sentences, Rob had assigned the largest piece of process work ever attempted, but Steve hadn't come down with the last shower.

He asked, "So what time frame did you have in mind for this, Rob?"

"Ah … well." Rob was sorely tempted to say 'yesterday,' but Steve wasn't fresh out of school either. He had worked at a number of plants and knew the score, as well as how much time and effort it took to understand and define the work of each person in a place as complex as a potroom.

"Okay. Let's say the top level view by end of next week, Steve. And, let's meet and see how it's developing on Tuesday." Rob wanted to stay involved in this. It was a foundation stone in his plan.

That was a good start to the day, Rob thought. He was walking down line 3 that was looking clean and tidy as usual, and Rob's eyes wandered to the potshells and conductors as he walked past and saw what he hadn't expected—bulging sidewalls and air on collector bars (six pots) and three pots cut out and waiting for dig-out—along the potroom.

Pots at Risk of Failure

Pot integrity is a term used to describe the soundness of a pot in terms of any increased risk of failure in service. If molten metal or bath finds a pathway to exit the pot, either through the sidewalls, the cathode, or through gaps between the refractory materials in the pot lining, the loss of liquid from the pot will quickly cause a loss of electrical continuity. In other words, current is no longer able to flow from the anodes to the cathode because the anodes are no longer immersed in the bath due to liquid level loss. Each pot takes two or three days to rebuild with refractory and cathodes, and even two to three simultaneous pot failures at a smelter can overwhelm the resources available to keep all the pots in the electrical circuit. So, maintaining and managing pot integrity in a potline of 200 to 300 pots is a key lever in the potroom process, with respect to cost, safety, environment, metal quality (iron contamination), and, of course, production rate from the potline.

Pots typically range in cost from US$100,000 to $300,000 in materials and labor cost to construct, a cost that is incurred every time a pot fails. The spent lining material of each failed pot is hazardous waste that is currently stored mainly in warehouses at each plant or in clay-lined landfills, awaiting suitable processing to make it safe for disposal. In the past decade, it has become evident to most companies that such a process involves recycling the spent lining materials in a carbon fraction, and a separate refractory fraction into existing bulk material processes, such as steel making (carbon material can be used as a fuel source) or into cement making (both the carbon and refractory cuts can be used in some cement factories depending on the sodium content of the aggregate).

Unexpected pot failures (tapouts) are a key source of risk for both employee safety (in managing unplanned, hazardous events, such as release of molten metal onto the floor) and potline integrity, the worst case scenario being loss of a potline if the aluminum bus work is too badly damaged (e.g., the Bayside smelter in Richards Bay, South Africa, in 2004). Pots that tapout typically cost more to replace, depending on the damage done and the extra time needed to rectify it. Pots that operate with compromised integrity (damaged cathodes, collector bars cut, sidewalls corroded) also require more power and additional attention from operations' staff, increasing workloads as well as the risk that accidents/incidents will occur.

The rate and predictability of pot failure can have adverse effects on potline metal production, as there are limitations on material supply and reconstruction staffing. If the failure rate exceeds the maximum rebuild rate, the consequence will be many fewer pots in circuit at any one time and, therefore, less metal produced.

Maintaining and managing pot integrity depends on a number of processes within the smelter and influences the health of the entire potline profoundly over time. This is illustrated in Figure 7.1 in a variation tree. The arrows indicate the direction in which variation is induced. The detail of this tree shows the way the key operating procedures and parameters influence the energy balance through bath superheat. The superheat, along with the temperature then have the major impact on the pot integrity, and the processes of potline power supply, pot replacement and control of metal purity.

Control of pot integrity needs to be addressed on a broader front because it also is impacted by the physical maintenance of the potroom as well, and by the monitoring and responses of the operations crews to changes in the mechanical condition of pots.

These complex interactions are shown in the cause and effect diagram in Figure 7.2, along with possible solutions and pathways to improving pot integrity. Successful organizational mechanisms to achieve this improvement always involve the accountability of the operations crews for monitoring and responding to the condition of individual pots on the basis of their individual risks of failure.

The risk of failure is a cumulative probability based on the deterioration in pot integrity over a pot's entire life due to the following:

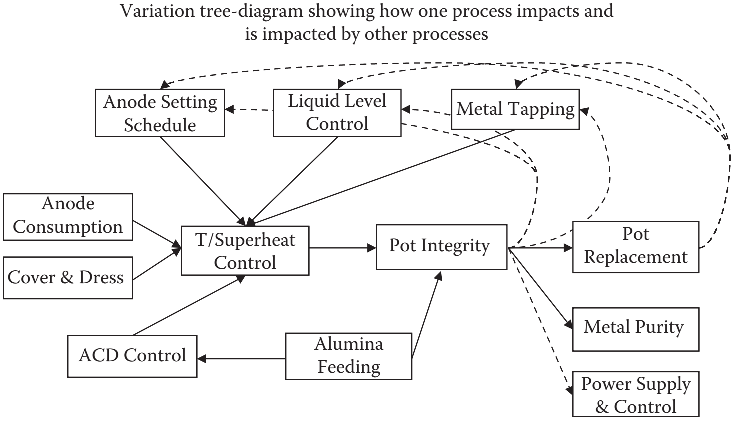

FIGURE 7.1
Variation tree for pot integrity based on the potroom processes that affect it, from brainstorming at a smelter. ca. 1990.

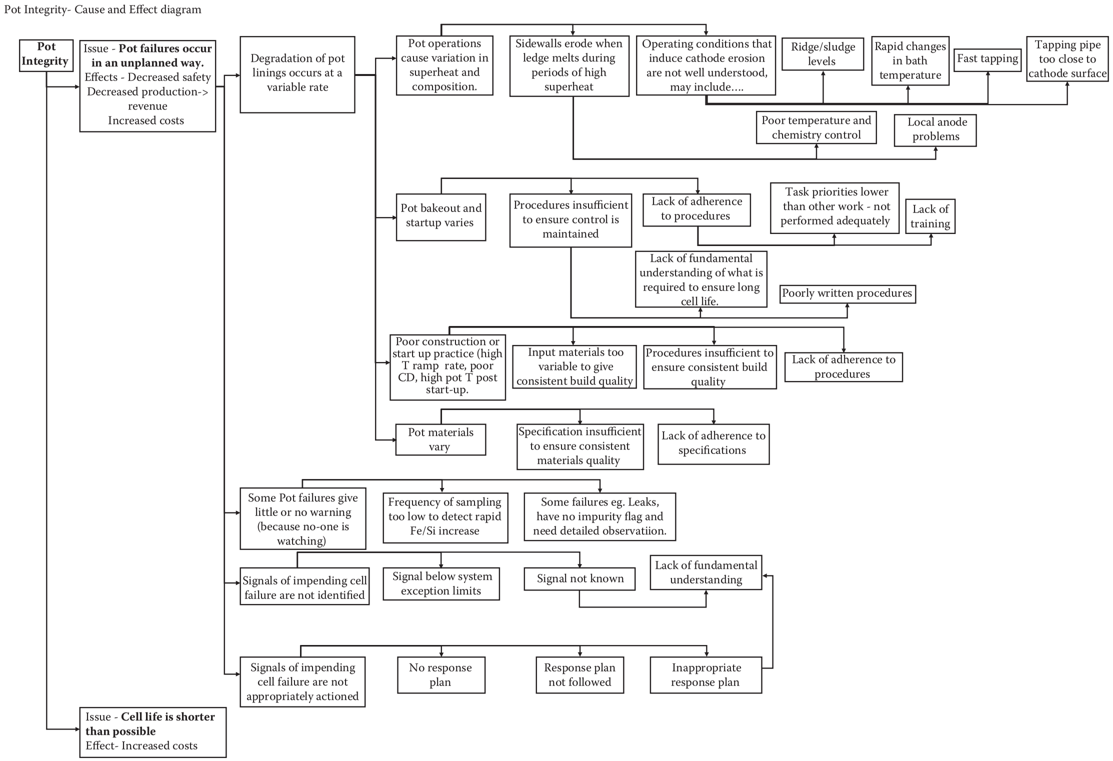

FIGURE 7.2
Cause and effect diagram for pot integrity: The process by which pots are controlled so that they will not fail unpredictably or lose performance over time as they age. Frequently identified causes are illustrated in bold boxes.

- extreme cycling up and down in bath temperature (e.g., from 980 to 940°C);
- periods of time when the cathode becomes frozen with bath inside, signaled by noise;
- anode spikes or burnoffs that can damage a cathode locally;
- sludge that freezes and becomes a permanent "ridge" on the cathode (long-term noise);
- damage to the cathode lining due to leakage of bath and metal, and heaving of the refractory materials due to chemical reaction with the molten metal: high Cathode Voltage drop (CVD) and/or cathode heave;
- cracked, corroded, or otherwise damaged cathode blocks, causing long-term iron contamination of the metal (Fe >0.2 for a period of time);
- deteriorated collector bar to bus bar contacts, or riser bolted joint contact resistances (poor collector bar current distribution); and
- damaged or corroded sidewalls, often flagged by loss of silicon carbide refractory (silicon in the metal, or repeated high sidewall temperatures above 400–500°C depending on the technology).

In fact, the damage to pots is analogous to damage to human beings. Every pot has some damage, but it is not considered to be "at risk of failure" unless there are certain threshold characteristics breached, such as Fe% >0.2, or sidewall temperatures persistently above 400 to 500°C. So, the management of the pots at risk of failure requires a database that contains these and other more specific flags and updates them daily so that pots that become damaged come onto a monitoring list in each part of the potline. Completing the previous analogy: a human being with a medic alert bracelet receives targeted assistance when early signs of a health problem are observed, and this is also the best process for a pot at risk of failure.

These at-risk pots should be labeled in some way so that the shift operating staff can respond to problems with this condition in a way different than the other pots that are not damaged. In particular, it is possible under this monitoring system to avoid excessive voltages on at-risk pots, apply special, higher feeding rates to them, and, if necessary, remove them from the potline circuit before they tap out.

This last response is most important because it prevents tapouts of pots on the potline. The number of pots that are in the at-risk category and are likely to tap out also provide specific guidance for how many pots need to be reconstructed in the coming months, and also which pots need to be removed from circuit to cause the at-risk group to decrease. This should be a constant source of concern for the production manager, but, in most smelters there is no monitored list of pots at risk of failure. Consequently, the failure of a pot is often a surprise and never a pleasant one.

In general, it is found that a *pot at risk* list of greater than five in one potroom is near the maximum that can be handled without tapouts and/or loss of a number of pots in a week, causing an inability to reconstruct them and loss of pot production days.

Using this method, it is possible to operate smelters with multiple potlines with zero tapouts for a number of years (e.g., Boyne Smelters in Queensland, Australia, in 2001/2002). The consequent reduction in operating costs is in the range $0.5 to $1 million per year, in the case where the power contract is not take or pay. If the power contract is take or pay, the cost of lost production is much higher because it also includes electricity that is paid for but not used. In this latter situation, the benefit of a planned cutout rate based on the number of pots at risk of failure is in the range $2 to $10 million per annum per potline.

Things can change fast in production. Surely, it wouldn't always be that way, though. Rob walked to the crew leaders' office, his pace accelerating as he saw other pots that were at risk. Why didn't I see these before? Then, wait a minute. Why didn't anyone else?

"Barry, I want you and Ford in my office in 10 minutes. See you there." Rob was already turning around.

"Sure, Rob. I'll have to find him though. I think he's helping on a problem pot cutout right now." Barry was on the two-way radio (RT).

Rob turned around. "A 'problem pot' is being cut out? We already have three pots out on line 3, and how many on lines 1 and 2?"

"Ah, counting this one, its 10 pots out, Rob. Those guys in reconstruction just aren't keeping up with us." Barry was matter of fact. It wasn't new information.

Ford and Barry were looking uncomfortable. Rob' voice was level, but there was something different about his eyes.

"So, Ford, whose responsibility is it to keep the pots in circuit?"

"We operate them," Ford replies. "Reconstruction builds new ones when we need them. So, it's both departments. Just like with carbon consumption. It's both departments. So, I guess it's really the GM's responsibility."

Now it was Rob's turn for deep breathing. There was apparently no one responsible for keeping the production complement of pots in circuit. "Okay, so where is our cut-out schedule, so that reconstruction can plan when to dig out each pot, and when to have the next pot ready for installation by us?"

There was a silence. "We don't do it like that, Rob. We try to keep them in circuit as long as we can. Then, we cut them out, or sometimes they tap out, unfortunately." Ford said the last word as if tapouts were pure bad luck.

"And, who pays for the 10 pots of metal production we're not making at the moment? And the 15 MW of power we're not using?" Rob was starting to get excited, not in a good way. There was a potroom process here that wasn't even on the radar, let alone on a chart.

There was a pause as the guys thought about that. Rob let the pause grow long into a silence. Thinking time … it seemed like there hadn't been too much of that going on.

"Ford, I want you to make a prioritized list of all pots that are at risk of failure out there, by line and with the actions that are being taken to keep them in circuit. And, I want to know which ones should be taken out of circuit in the coming weeks to eliminate a risk of tapout. I mean eliminate it. And, I want the names of the people who are now responsible at a shift level for operating this system."

"Eliminate the risk, Rob? I don't know if you can do that," Ford said with uncertainty.

"If we can't do it, then we have to accept the chance of bus bar failures, molten metal explosions when liquid metal contacts wet materials outside the pot, and people getting badly injured, Ford. That's not what we joined up for, is it?"

"Okay, no tapouts Rob!" Ford was walking out with Barry.

"One more thing, guys. I want all pots back in circuit, except for one, in one month's time. And a cutout schedule published and updated each week. That will be managed by Steve. But, he will need your "at risk pots" list and your authority to cut pots out."

Now for the painful part, thought Rob. He had to tell the general manager that reconstruction would need one more crew for at least the next three months. There was obviously a queue of pots that were operating with damaged cathodes and were at risk of failure. That could be 30 to 40 pots (in fact, 33 pots as he found out later). That list needed to be less than 3 to 4 pots per line, Rob thought, or the pot controllers wouldn't be able to keep their eyes on them to prevent tapout, and because two pots coming out within a week would still overwhelm any normal reconstruction resources and schedule.

So, that was an extra 20 to 30 pots that needed to come out of circuit in the coming months, plus the 10 that were out now. This would take some time, Rob thought. He wondered what the efficiency of those at-risk pots was right now. It wouldn't be a pretty sight. Their current distributions and noise levels would both be disturbed. Now, the broad potline distribution of pot noise with the long tail of noisy pots was starting to make sense. And where was the budget for the extra pots to be reconstructed? It was upwards of an extra $4 million.

"Problem Pots." There was the old culture alive and well in potroom language he thought as he walked across to the general manager's office. But it wasn't the pots that were the problem; it was the way they were managing them.

However, Rob thought he would probably hear that again real soon, as he knocked on the GM's door.

Tuesday came soon, and Rob was sitting with Steve looking at a large printout of the flowsheet.

"You see now we have the Inputs, Outputs, and the Production Outcomes on this chart, Rob. And, the processes are listed in the center of the flowsheet, with the pots at risk of failure in there as a process, which is one the guys never had before and still don't really want."

Steve had done a lot of work on this and had covered all the crews as well as Ford and the rest of the operations team.

"So, what tells us if each of these processes is in control, Steve? How do we know if there is a problem on the way?" Rob asked the question he had been asking for a couple of months now.

Steve looked at the chart. "Well, if the processes are managed right in the first place, we don't need any more graphs, do we, Rob?"

"If the processes were managed right, there would already be control points and charts showing whether or not they are in control, Steve. That's why we're doing this. We don't even know whether all of these processes are recognized, let alone managed."

The penny was starting to drop for Rob. Even after the events of the past six months, there still wasn't a ground swell or even a light bulb going on for changing the way potrooms were managed.

"Let's get the flowsheet and the control charts completed first, Steve. Then we can review these key control points with the whole team. Maybe we might see what nasty surprises the next six months could bring and take some pre-emptive action for a change." Rob gave the flowsheet back to Steve with more red ink on it than black.

Potroom Process Flow

The chart in Figure 7.3 depicts the process flowsheet for a prebake anode smelter. Some technology-specific issues may change details of the inputs and outputs slightly. However, the processes and their control points are generic, the same for most smelters.

In the potroom, as in other complex chemical plants, there is not a one-to-one matching of inputs, processes, and outputs. The majority of processes take place inside the pots and, therefore, are influenced by many inputs and, in turn, influence a number of outputs. The production outcomes listed in the chart, therefore, are also a function of multiple processes, although they are somewhat aligned with processes and physical outputs. However, these outcomes *are not directly controllable*, although the desire to control them rather than the processes is a frequent mistake by management—known as *management by objectives (MBOs).*

Therefore, what is crucial is that each process has at least one key control point, which can be responded to by the person closest to the process and charted over time across the pot groups and potlines at a frequency appropriate to the response time required.

Some of these control charts have been given in chapter 5 already. Individually, they allow a statistically valid decision to be taken concerning when any one process is losing control, requiring diagnosis of cause and response. Responses to these out-of-control signals are often

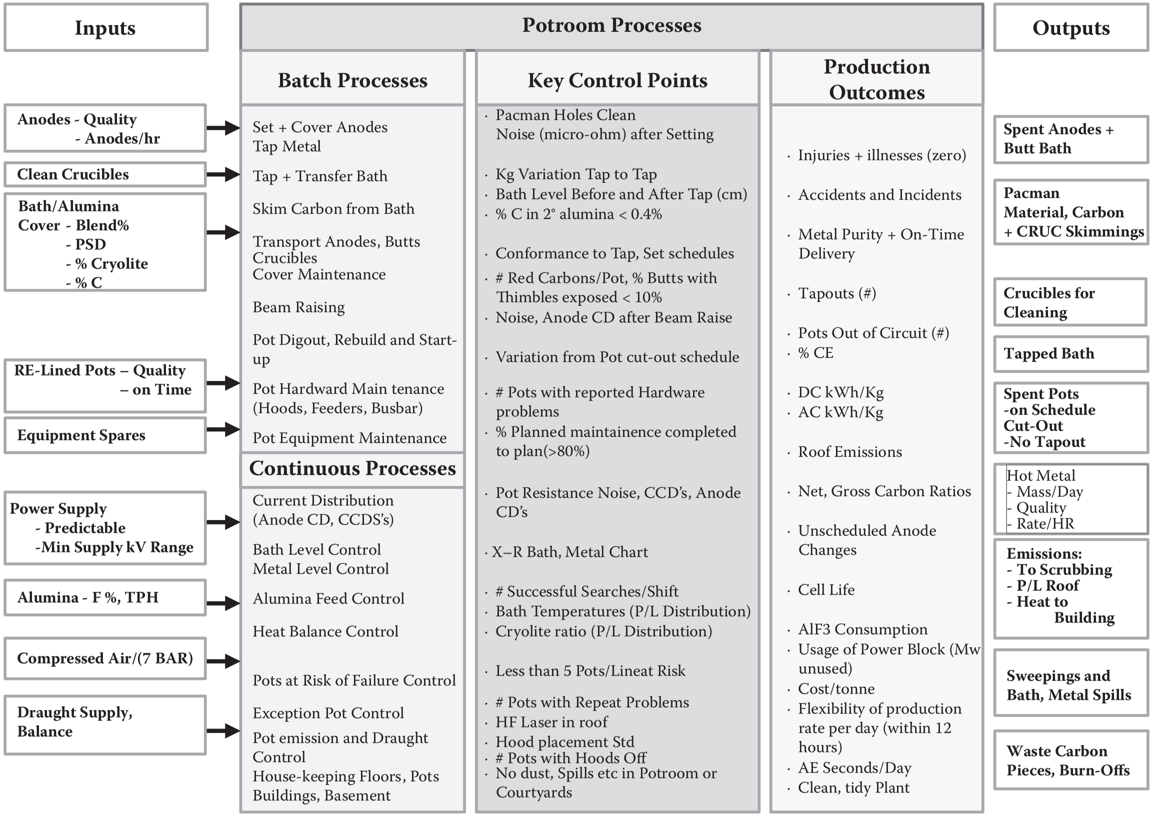

FIGURE 7.3 (See color insert.)
Potroom process flow chart showing the key processes and their control points for the production of aluminum.

multilayered, with a rapid, protective response usually required to prevent damage, while the diagnosis and corrective response is initiated based on in-depth analysis of more than one control point along with "drill downs" and may take days or weeks to complete.

Wherever possible the corrective response needs to ensure that the problem does not recur in this or other parts of the potlines; in other words, the cause is systemically eliminated. Where control responses do not achieve this goal often enough, problems recur, and the number of problems multiply over time. Diagnosis of problems then becomes more complex because of the large number of potential causes still "active" in the system.

This is a general characteristic of industrial that is made much worse in potlines because of the large number of production units. If each pot is allowed to develop its own peculiar fault condition, e.g., cathode connection defects or solidified ridge on the cathode, the management of the potline as a whole descends into a reactive struggle with sick or unstable pots, and the potline production resources are quickly overwhelmed.

The strategy for process management of this type of system is discussed further in chapters 8 and 9. The most critical aspect of this strategy is that, for the above reasons, it must be proactive. Causes of apparently small problems need to be identified and removed before they permeate a larger proportion of the pot population. This means that specific control points must be explicitly monitored for each of the potline processes/operations and responded to quickly, so that the number of problems always remains manageable for staff, and so there is enough time to get to the actual cause of problems. Otherwise "protective," compensatory responses become the only resort (ambulance at the bottom of the cliff). The monitoring of these control points is informed by our understanding of the variation—pot to pot, section to section, crew to crew, etc. However, the responses to problems draw much from individual experiences of operators and maintenance staff. Accessing and documenting these rich response experiences are essential to plant improvement and is another reason why a formal process management system is necessary.

In the above discussion, it should be noted that feedback control based on potline outcomes is almost always too late to avoid serious damage to a process. Instability in the chart for one or more key control points provides a trigger for immediate response. But, this is still likely to give delayed feedback to a process with significant time lags.

Earlier warning signs of loss of control are valuable, and ultimately feed forward control should be implemented around these warning signs. Please refer to Table 5.1 for examples of these early warning signs.

Rob scrutinized the flowsheet. It seemed to represent the potline processes well, although he had no doubt that it would be built on over time. So the guys *did actually know* how it worked—when asked to write it down, they could do it.

The new element in the chart now was the introduction of some specific control points that he could test the processes against each day, and which would provide feedback to the owners of each process through trends or reduced variation over time. For sure, some of them were not where they should be. For example the percentage of anode butts with thimbles exposed was running as high as 30% on some days in the rodding room. This was just by Rob's eyeball as he walked along the power and free conveyer carrying the cleaned anode butts. It wasn't even a measure the plant collected at the moment, and neither was red carbons in each pot, or the number of pots with hardware problems. But, there were plenty of those as well.

So, the key action was to get the measures in place and visible and to get one person (a process owner) accountable for maintaining and responding to each one. The next thing, Rob thought, was to get each measure stable day in and day out, which was more important than trying to hit targets when you couldn't even predict tomorrow's result. That, at least, would allow the team to focus on improvement rather than lurching from one disaster to another, trying to recover.

But, there was something else that couldn't go on the flowsheet. How were people reacting to the present control systems that were already in place? Everybody knew that pot resistance noise and anode and cathode distributions were important, and cryolite ratio was already a key smelter control for heat balance.

So, why was the cryolite ratio allowed to drift downward in the superheat excursion earlier this year? Why wasn't that a signal that was responded to, and wasn't finding the cause already part of the way the smelter should operate?

A feeling in the pit of Rob's stomach. And a question: *What else was needed?*

Identifying Psychological Precursors

Psychological precursors can be thought of as "latent states," which may determine how individuals respond to stimuli such as work responses. But, can these states be detected or predicted? There is certainly no way to know what people are thinking.

What can be defined are the behavioral indicators and also the strongly held beliefs that are shared across the workforce at a particular site.[1] These shared mythologies form the workplace culture and are the result of the way the plant systems and decisions have been operated over a long period. The Fallible Decisions[2] of senior executives and the (related) deficiencies of line management combined with the opinion leaders and other cultural influences of the people at the site. For example, a common mythology that develops at production plants is "Managers only care about production."

Identifying these staff mythologies and creating new mythologies about safety, for example, gives management the legitimacy to address

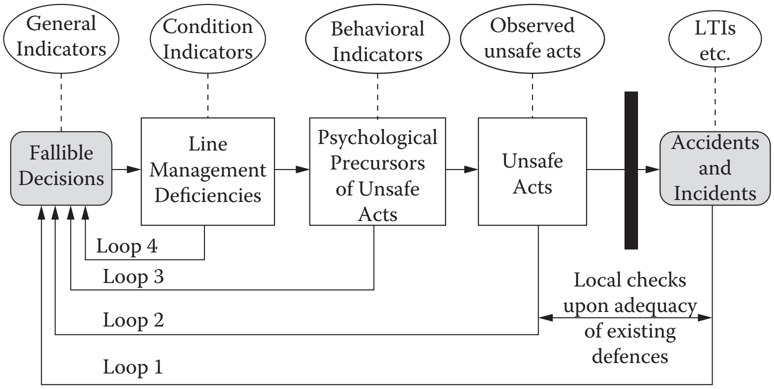

FIGURE 7.4
Actual and potential feedback loops associated with the basic elements of production. (Adapted from Reason, J. 1990.)

the plant systems that influence safety, including the latent, embedded errors in the plant control systems. The diagram in Figure 7.4 from James Reason[2] demonstrates the link between fallible decisions and accidents (or other forms of loss of control), and the potential power of the psychological precursors if this information is received clearly by management (control loop 3).

Psychological precursors or preconditions (latent failures) are thought of as "resident pathogens," and may be introduced anywhere within the production system by humans, leading to a wide variety of unsafe acts and misjudgments. These pathogens can be minimized by employing a skilled workforce that is alert, knowledgeable, and motivated. Nevertheless, high workload, undue time pressure, error proneness, susceptibility to stress, ignorance of hazardous situations and systems greatly increase the chance of latent failures. In terms of safety control, Reason[2,3] stressed the importance of the following:

- A sensitive multichannel feedback system
- A rapid and effective response to actual and anticipated changes

It is evident that all feedback loops 1–4 can be sheeted back to the "Fallible Decisions" of management. Everyone is occasionally guilty of incorrect decisions, and this will not change. However, the nature of the control system shown in Figure 7.4 is that frequent feedback about the consequences of decisions are fed back to the people who make them. Because of this feedback, a single fallible decision is not going to cause consistently poor management. Therefore, the problem we are really addressing in loops 1–4 is one involving *patterns of fallible decisions,* despite the numerous feedback loops, which are driving poor control through the entire business.

The question then becomes: What guidance do senior managers have to reduce the risk of these patterns of decisions? This is a question about management philosophy and more specifically about manufacturing philosophy. W. Edwards Deming's book. *Out of the Crisis*,[4] was written in response to an aimlessness in the philosophy about manufacturing. The revolution in Japanese manufacturing in the 1950s and 1960s is a matter of record, but the thinking behind it was not fully recognized elsewhere until Deming's book and famous seminar series in 1986. Some of the 14 principles espoused by Deming in his book are reproduced here from one of his seminars, to demonstrate what is, despite the passage of time, still the best starting point in manufacturing philosophy.

Point 1. *Create constancy of purpose toward improvement of product and service, with the aim to become competitive, stay in business, and to provide jobs.*

The stress here is on "constancy of purpose." Organizations that do not have this overriding purpose will flip-flop from management fad to management fad. They will wobble between worrying about quality and shift over to worrying about costs and then back again. Without constancy of purpose, people won't take chances because they will be afraid the rules will change again next year.

Point 2. *Adopt the new philosophy. We are in a new economic age. Western management must awaken to the challenge, must learn their responsibilities, and take on leadership for change.*

Adopting a philosophy doesn't mean it is simply given lip service. It means incorporating it into an organization's life. There will be natural resistance to changes brought on by TQM (Total Quality Management) that requires management to be more than "fair weather" believers.

Point 3. *Cease dependence on inspection to achieve quality. Eliminate the need for inspection on a mass basis by creating quality into the product in the first place.*

For manufacturers, inspection is clear. It takes place at the end of the process and is used to ensure that a faulty product isn't shipped to a customer. The only reason that inspection takes place is that enough defects have been discovered in the past so that processes can't be trusted.

Unfortunately, when error rates or quality deteriorates, the first impulse of traditionally trained workers and management is to spend more time checking for errors instead of attempting to improve the underlying processes: "We need to do a better job of catching these errors!!" versus "We need to figure out a means of reducing the number of errors in the first place."

Point 5. *Improve constantly and forever the system of production and service, to improve quality and productivity, and thus constantly decrease costs.*

Point 9. *Break down barriers between departments. People in research, design, sales, and production must work as a team, to foresee problems of production and in use that may be encountered with the product or service.*

Processes cut across department lines. For this reason, no single department or individual will understand fully any process. In order to start improving these processes, teams must be organized that include members from across the organization.

Point 11. *Eliminate work standards (quotas) on the factory floor. Substitute leadership. Eliminate management by objective. Eliminate management by numbers, numerical goals. Substitute leadership.*

This is probably the most controversial of Deming's 14 Points and the point most often ignored by managers. Numerical production standards are typically set by picking what an average person can do with a particular job. The problem with this is that half of any group will be below average and, therefore, will be doomed from ever being able to meet the standard. The above average half of the group will be pressured by their peers to produce to the average and no more. In the end, production will fall, half the work force will be panicked, and no one will be happy.

Through understanding the variation within production and process data and diagnosing the causes of this variation, quotas and numerical targets can be replaced by the team objectives of stability and capability of the process to meet goals month after month. Working on these underlying issues and measuring performance on this basis are huge change, and can only occur if top management exerts strong leadership of the changes What is often forgotten is that these changes also require constancy of purpose over a long period (**Point 1**).

The team had accepted the new control accountabilities and the plan Rob had outlined to implement them. But, as he drove back along the straight, the questions didn't leave him.

What else had to change before a new culture of production control could take hold?

Exercises

1. What is the control point for the pots at risk of process failure? What should the response of the potline superintendent be if this control point is breached?
2. Name six "drill down" signals that indicate that a pot is really at risk of failure?
3. What is the starting point for management of a manufacturing or processing plant, even before consideration of the customer's needs? Why is this so important for the staff of the plant? Discuss in groups.

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8

Start of a New Culture

"Fire brigade, now. Powder only. No! Not water. No water at all." The crew leader's voice was shaking.

The General Purpose Crane (GP) driver had driven over a pot reconstruction operation in line 1 with a full crucible of metal. And miscalculated.

The best part of two metric tons of metal had spilt on the hydraulics of the Hitachi digger. The fire raged up the digger and into the roof. Beneath it, the potline bus bar was starting to warp on the operating floor, and there was molten aluminum in the basement below the pot being excavated.

Rob had been called at 1 a.m., and it was now almost an hour later. Rob was standing out on the line with Ford.

"Take the line down now, Ford, and get the earth trolley moved here. Ring all of the day shift. We're going to clean up this mess." Rob was surprisingly calm. In his mind there seemed to be plenty of time.

For two hours they worked on the line. The digger couldn't be saved, but the potline bus bar continuity was holding, with all the available cooling air on the wedges, which were the cutout points for the pot. The current was slowly restored at a little after 5 a.m., and the potline was stable before lunchtime.

No one hurt. No pots were lost. A minor miracle, Rob thought. But, there was a problem.

"We're behind almost a shift on anode setting, Rob," Ford remarked. "And tapping. We need to catch up. We're bringing back the PTM (pot tending machine) from maintenance. We just need your authority to resume operations."

"What's the potline electrical resistance, Ford?" Rob knew the answer, but he wanted to hear it from him.

Barry answered first. "Well, it could be better, Rob. We have to take care on the manual operations. We don't have much resistance to Earth, and the neutral point is close to the digout pot."

"Right, Barry. So, no we won't be starting operations at the moment, will we? I want to know where the Earth leaks are, right now and how we're going to remove them, what job-specific insulation requirements. Plus that requires, and then I want the line resistance back up to 5,000 ohms."

"We don't even get that on some rainy days now, Rob. This means we'll get further behind. We might not be able to catch up." Barry was calm but insistent. He had been there before.

Rob didn't hesitate. "We'll be taking a miss day, Barry, no setting and no other operations. We have that long to find out where the leaks are and fix them, or eliminate the electrocution risk. Then, we can resume operations.

So, you had better get started. Give me your nominations for the Earth Faults Team in an hour, Ford. Including an electrical expert."

"Another thing, Ford." Rob was keeping his voice level. "I want you to lead the investigation team to look into this incident. Starting now, not later. This was a potential fatality, in fact, multiple fatalities. You will need to interview all of the staff involved for a start. Take Steve Harris and also the reconstruction superintendent as team members, and an expert GP driver as well."

"Shouldn't we wait until we're back on schedule with operations, Rob?" It was the answer for which Rob had been waiting.

"Well, we won't have any operations if we keep on trying to kill our staff, will we, Ford? So, no, I guess not. The investigation starts right now. I want a preliminary report tonight." Rob was already walking away.

The next week was a blur of investigation, questioning, and more investigation. Not the first time a crucible had gone over a reconstruction crew. Not the first spill. Not the first time an electrical hard Earth had been let go, until there was a more convenient time to find it. Which there wasn't.

Each potline crew member made a personal appeal to Rob, on behalf of the GP driver who had spilled the metal. Not one person mentioned the digger driver, though. He had climbed out on the top of the digger onto a platform at the tap end before the flames reached him.

Sitting in his office that night, too tired to drive home, the question came back to Rob unbidden: *What else has to change?*

However, maybe the answer was there in the interviews with the crew members; the response to the digger incident spoke volumes. Production was still king.

Friday afternoon, 3.45 p.m. Light at the end of the tunnel after a long week. The guys on the floor were responding to the safety auditing changes and the new priority of safety as equal to that of production—they went hand in hand or not at all. The new Safety Committee had wide responsibilities, with representatives from each crew including maintenance, and they met with Rob each month. The process charts were almost all in place.

Rob looked at the newly designed charts on pot temperature across the potlines. Some high temperatures (970s and 980s) were evident from a 66 pot section on line 2. About 45 minutes before the dayshift operations wrap up, Rob thought, including fluoride scheduling for the shifts over the weekend. Five minutes for closer inspection showed:

- 12 pots out of 66 over 975°C today: one quarter of line 2; and
- 11 pots out of 66 on line 1 also over 975°C on Thursday. At that stage no special actions triggered. Was that significant? The chart said "investigate."

So, about 17 to 18% of pots, compared with a historical, average hot pot percentage of 10% or less normally.

Rob recalled the Repeatability and Reproducibility study had shown that the detection of pots >975°C was now 90% accurate, which was considered to be good. It might be even better if the feed cycle and the anode setting cycle were taken into account in the measurement process, in the future. Temperature variation along the pot and also between overfeed and underfeed cycles were both about 5°C, or sometimes more.

One glance at the average temperature and AlF_3 charts didn't show a trend, but Rob knew from the previous experience that the overall potline averages didn't respond much until a substantial number of pots were affected.

The present plant situation flashed into Rob's mind:

- 7 pots still out of circuit
- 11 pots with cut collector bars spread across the lines
- Air on 13 sidewalls and not much spare air volume
- 200 metric tonnes down on plan this quarter.

In the same second, Rob's mind shot back to the consequences of a serious loss of temperature control:

- Temperature run-away on many pots or a whole potline within a week
- Anode cracking, especially with the longer anodes they had now
- Cathode or sidewall failures on the damaged pots and new damage on many more
- Loss of current efficiency for a period of weeks after the temperature spike
- Potential loss of control of a potline if some "sick" pots result

There was sweat beading on Rob's brow. The temptation to ring the fluoride scheduler directly was almost overwhelming. Rob's hand was on the phone.

3.55 p.m. Was this what Ford and Steve were reacting to daily when they "dealt with a problem" before it became serious. You never heard what the cause was or whether it had actually been a problem. Just that it wasn't anymore.

Rob remembered his unanswered question: *What else has to change?*

There was an answer. But, there was also a test. Ford and Steve were outside in the corridor. They had seen the data, too.

Assessing Probabilities Using Bayesian Statistics

The actual probability of any/all of the above potline consequences is quite low, in fact, considering the number of times that potline warming is identified in smelters and the small number of actual losses of control that result. However, Cass Sunstein[1] When quoted in Kluger's article in *Time Magazine*, noted that "When confronted with things we dread, the more we dread, the more anxious we get, the less precisely we calculate the odds of the thing actually happening."

This phenomenon is called probability neglect. The minimization of possible loss dominates the thinking. Even though the risk is unknown and although some more analysis could quantify it, the mind focuses on the dreaded consequences.

Therefore, in the present situation, it is likely that management will order a special, larger adjustment of the AlF3 addition rate, although the data provided are clearly incomplete and no more in-depth investigation has taken place. So, the question we need to ask is: Does an analysis of the data support such a response from the potroom manager?

SOME BAYESIAN STATISTICS

Let us assume that the true, *a priori* probability of pots being above 975°C is 10%. So, out of 66 pots, there are 7 (6.6 before rounding) pots that are actually hot and 59 (59.4) pots that are not.

However, the detection method is only 90% accurate, leading to a probable error in the detection of pots less than 975 of $0.1 \times 59.4 = 5.94$ pots that are measured as hot when they are actually normal.

Furthermore, out of the 6.6 pots that are actually hot, one pot will probably be detected as being less than 975°C (0.1×6.6), and 5.94 pots will be correctly detected as hot.

So, 11.88 pots will be detected as hot, while only 6.6 are truly above 975°C. This is the same result as reported to the potroom manager on Friday afternoon and shows only a (5.94/11.88) 50% success rate in picking the hot pots.

More seriously, though, the percentage of detected hot pots in this relatively small sample of pots (66) has increased from 10 to 18%, which gives the appearance of a step change in hot pots. This same figure is the one that is exercising the potroom manager's mind.

The above calculation shows the danger of responding to a change in a minor percentage of exceptions, especially when the accuracy of detection is not very high. However, it may not be a calculation that is immediately available to the potroom manager.

STATISTICS AND PRESSURE

On this Friday afternoon and in any case where data must be interpreted and a decision made in real time, there are two risks that exist and that must be weighed in the decision:

1. Type 1: The risk of responding to a false alarm. In the present case, this is the risk of responding to pots that are not hot (but are detected as such) and, more critically, the risk of responding on a line basis to an apparent increase in the number of hot pots when there really isn't one.

2. Type 2: The risk of not responding when there is a real change occurring—called the "failed alarm." This is often where the "dread" consequences and probability neglect take over in an operationally based person. The negative, dread consequences, even if only fully experienced once, are never forgotten.

Going back to the true probabilities of hot and normal pots, let us consider the "signal" the potroom manager is looking for as the 6.6 hot pots, and the "noise" is the 59.4 normal pots.

What is the signal the manager actually seeing? Six (5.94) out of seven (6.6) of the truly hot pots are detected; the probability of a "hit" is 0.9. One (0.66) of the hot pots will be missed, however, so the probability of a missed signal is 0.1.

The four probabilities define a response matrix for any situation (Table 8.1).

This information may be readily represented by Figure 8.1. In this case, "noise" consists of the 59.4 cold pots, and "signal" consists of the 6.6 hot pots. "β" indicates the "response criterion" that defines the false alarm probability tail of the noise distribution and the failed alarm tail of the signal distribution.

The demonstrated sensitivity in distinguishing a hot pot here is called the separation, d′ between the noise and the signal (derived from the 90% accuracy figure assumed earlier). Given this separation, the probability of a false alarm in the case of a 975°C cutline (represented nondimensionally by β) is 10%, and the probability of a failed alarm is also 10%. In other words, the cutline hits the tail of both signal and noise distributions in the same place in this case.

These probabilities apply to each of the 66 pots individually, but the aggregated potline process has only a small proportion of hot pots (normally about 10%).

As the Bayesian statistics showed, the above scenario can almost double the number of pots that are found to be hot because the much larger proportion of normal pots are subject to the same 10% error in the

TABLE 8.1

Response to the Signal (Hot Pots) and Noise (Normal Pots) on the Quarter Potline

		Signal	Noise
Response	Yes	Hit (p = 0.9)	False Alarm (p = 0.1)
	No	Miss (Failed Alarm p = 0.1)	Correct Rejection (p = 0.9)

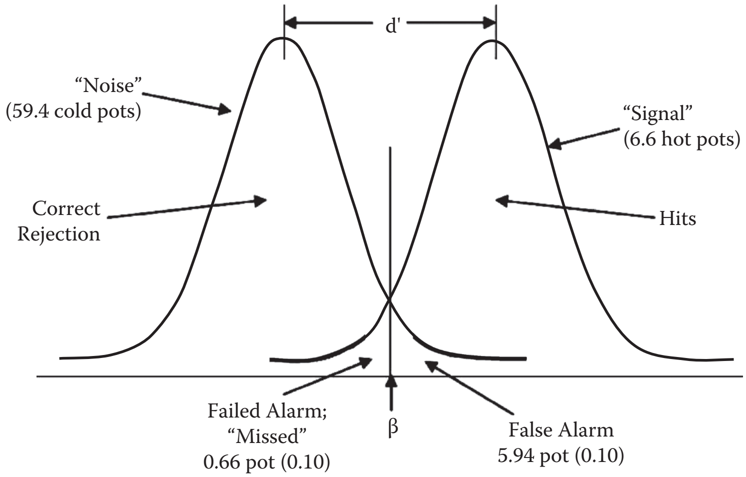

FIGURE 8.1
Curve representing "signal" and "noise," p (Hit), p (Miss), p (False Alarm), and p (Correct Rejection).

hot/normal pot distinction. Therefore, the cohort of hot pots as detected here should be treated with caution.

Can the potroom manager improve his or her decision making by reducing the probability of a false alarm? This could be done by counting only the pots above 980°C, for example. This represents a movement of the β response criterion to the right in Figure 8.1 and would decrease the false alarm probability back toward 5%. However, it also would increase the probability of a failed alarm or "miss"—the chance that a real increase in hot pots is occurring but goes unnoticed. Such a temperature increase would then be further advanced on a larger number of pots before it is recognized and action taken.

Increasing the separation or sensitivity of the hot pot distinction is the more sensible path in this case, because a failed alarm has the more serious immediate consequences and its probability on individual pots is already 10%. *This might be done, for example, by retesting the 12 (11.88) pots measured to be hot.*

Given that some of the normal pots were probably undergoing a warmer part of their feeding, anode setting, or tapping cycles when the first temperature measurements were made, it can be expected that retesting the temperatures on all 12 will lead to better distinction of the 6 normal pots, with most being reclassified as normal. However, this practice takes some time on a larger group of pots, and building better sensitivity into the measurement process upfront is a much better proposition if it can be achieved.

"We got about a half hour, Rob." Ford was ready to act.

Rob thought that additional AlF_3 would probably cause some cold pots next week, but there would be fewer hot pots over the weekend and no losses in pots (some were being held in circuit at the moment). Something wasn't right though. Were they really sure about the number of hot pots?

"Ford, what do you think the chances are of being wrong about some of those 12 pots on line 2, section 3?"

"Well, the measurement is pretty good with these new thermocouples, so I reckon it's right, Rob. And, we had the same thing on line 1 yesterday."

Which no one even noticed and today they are back to normal, Rob thought.

"I want each of those hot pots on line 2 retemp'd. Now, Ford."

"Steve, I'd like you to look at how many of these +975°C "hot pot signals" we've had in the past six months, and how many of those actually amounted to something after that. We meet back here in one hour."

"Okay, Rob. The scheduling will be done for the weekend by then, though." Ford let the statement hang in the air.

"That's right, Ford. They won't be needed. We're going to find out what is actually going on, if anything, and then treat the hot pots on shift as necessary. I expect all of the new information about this to be handed over to the pot controllers on night shift, so they can continue monitoring, especially the 'at risk pots' we have. We do have pot controller handovers from shift to shift, right? With the data I mean?"

Ford answered honestly. "Ah, not like that, Rob. It's more like a check if there are any problem pots to look after."

There was that phrase again. Despite the situation, Rob smiled. Now they were getting somewhere.

It was after 7 p.m. when Rob got into his car. Only 7 out of 12 of the hot pots originally detected had actually been hot. Situation normal. In fact, there had been 19 "hot pot" signals on at least one 66 pot section over the past six months, close to one a week. Only 8 were actually picked up, and all of those had been smacked with big hits of AlF3 on the whole line, with miss metal taps, and closely followed by high potline taps the next week. One of the AlF3 hits was right before Rob's first superheat excursion. Who knew if it had actually been the cause?

Of the 11 so-called "hot pot signals" that had been missed completely, not one had given rise to a real change in potline temperature or AlF3 concentration. They were all noise and no signal.

Learning the hard way, but not before time. Ford and Steve had looked shell shocked. Their world was changing. Instead of taking a lift with Rob, they both stayed at the plant to talk with the night shift crew to explain why the so-called "hot pots" hadn't been given extra ALFs.

Exercises

1. What is the preferred fire extinguishing medium in the potlines, and why?
2. Why is there a risk of making the wrong decision when looking at the number of pots above or below a threshold temperature? Explain in terms of the distribution of pots in the normal (*noise)* distribution and those in the abnormal (*signal*) distribution.
3. Under what circumstances would you want to have more failed alarms than false alarms in a process? More false alarms than failed alarms?

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9

Reformulation of Potline Control

"What's happening with the voltage reduction on line 3, Steve? We don't have power to burn, you know."

And burning it was. Rob now had the highest potline voltage seen on the line in recent years, and there apparently wasn't a single thing anyone could do about it. For five days, the team had been working on what was causing the voltage increase.

Steve Harris was hunched over the computer console, looking at the voltage numbers pot by pot, and looking much older than he did six months ago when he had started.

Nominal voltages hadn't changed, but the actuals had, and the driver was the noise voltage. That much was clear.

Before the process alert, the team had been half way through the work that Rob had set down for this month—a rethink of the control systems for the plant. Not the detail, but the "why." This work was progressing well, with a lot of understanding emerging about the difference between the way control was done now, compared to the way it should be done.

Process Control Reformulation: Part 1

From an overall control formulation viewpoint, the question is: Do we now understand what we require our control systems to do, and how do we commence their redesign? The liquid pitch heating system and potline control examples are both discussed.

Start by describing the sources of variability within each process, the constraints (specifications) that govern the safe process operating regime, and the degree of natural variation in the system that must be accepted and accommodated in the control:

A: HTF Process

1. Variability is due to many different sources, including the changing nature of both the HTF (heat transfer fluid) and the pitch itself.
2. Variability: The heat transfer surfaces have a changing thermal resistance, which will influence what total temperature difference is required across the HTF/pitch system and, therefore, the required target temperature of the HTF.

3. Constraint: The HTF cannot be heated above a certain temperature without risk of it cracking to smaller molecules and then possibly igniting.
4. Constraint: The HTF flash point should not be allowed to reduce below a certain point because of the risk of ignition in the vapor space. This flash point changes continuously over days/weeks as the HTF breaks down.
5. Constraint: It is not feasible to maintain the main heat transfer surfaces more than once every three months.
6. Constraint: It is possible to replace the HTF in the system once per six months, if necessary.
7. Due to the above constraints and sources of variability, the variation in target HTF temperature and flash point should both be less than 10–15°C.

B: Potline Process

1. Variability: Each pot is distinct and different in both mean properties and also variance. Pots, therefore, have their own automatic control settings, their own characteristic current distribution/stability, cathode electrical properties, and alumina feeding system.
2. Variability: These individual characteristics are dependent both on variability in the physical hardware and on the way the pots were started up and operated over their lives (like human beings).
3. Variability: The variation between pots is the greatest component of the potline variation, although the variation over time on each pot also is substantial.
4. Variability: Because of the presence of a solid, cryolite-based ledge around the walls of each pot, there is a strong dependence between the temperature of the bath and its composition with respect to solutes, such as aluminum fluoride. In fact, the entire pot process is characterized by a multivariate characteristic that responds poorly if one variable is used to manipulate others in a control sense (e.g., aluminum fluoride concentration being used to manipulate temperature made the plant vulnerable to process excursions—superheat, anode failure increases—as seen in previous chapters). This means the root cause of variations in heat and material balance must be addressed as the main mechanism for reducing these variations.
5. Variability: The natural variation over time and pot to pot can be kept within a 30°C band from 945 to 975°C, on 95% of the pots if all other manually maintained parameters also are kept in range, and the type of compensatory control demonstrated in the previous process excursions is minimized.

6. Constraint: Real-time control responses must be mainly automated because of the large number of pots. This includes detection and first stage diagnosis of causes of uncontrolled variation.
7. Constraint: Only pot voltage and current are observable continuously; all other measurements are manual and infrequent.
8. Constraint: Each pot has gradients in temperature, composition, and current distribution along the length, whereas measurements are only done at one position, usually where metal tapping is performed.
9. Constraint: Most of the work done is manually performed or assisted. Thus, most decisions that affect the pots are made by humans, and many of these may be unrecorded because they are discretionary within the SOPs (standard operating procedures) or are unobserved/monitored.
10. Constraint: Pots must stay within a 945 to 975°C, 7 to 12% AlF_3 thermal operating region to be operated safely. Likewise, the short term (second-to-second) normalized voltage instability must remain below 50 mV, current distribution between anodes and between cathodes should be even and steady, bath and metal levels within spec (bath above 14 cm always), and alumina feeding and anode effect termination (AET) must always be enabled (no empty hoppers, and with backup/emergency alumina feed control at the pot in case of central computer failure). Pots outside the above general conditions may become sick and unsafe to operate.

Within this framework of variability and process constraints (or specifications), the control reformulation for the liquid pitch heating system and for the potline process focuses on two formal control elements:

1. The Control Objective: For the HTF process, the control objective is to achieve the overall process heat transfer coefficient, U (to minimize the temperature gradient), and maintain both the HTF flash point and operating temperature within safe limits; for the potline, the control objective is to achieve electrical current distribution stability between the anodes, and also close to vertical current flow in the metal to the cathode blocks. This even current distribution and stability over time then provide pot voltage stability over time, allowing both the anode cathode distance and energy losses per unit production to be reduced.
2. The Base Control Mechanism: For both processes, the control mechanism must focus first on detection, diagnosis, and removal of causes of variation in the heat and material balance, both through human operating inputs, measurements, and decisions, and through automated sensing of abnormalities in

> the state variables (e.g., temperature). The maintenance of the process within the safe region defined by the constraints is then a much more tractable control problem.

Using the new descriptions of process variability and production or safety constraints, both of these formal control elements can be further defined for the target processes. This is discussed below for several potline subprocesses including alumina feeding control.

It is important to note that the traditional control objective of *maintaining the process at a fixed target level* and the traditional control mechanism of *feedback of a deviation in the control variable to cause an adjustment of a manipulated variable* need to be set aside or at least subjugated to reformulate the plant control system, because these control elements avoid the crucially important thought process about *the cause of the variation.* The traditional objective and mechanism, therefore, are not compatible with achieving the purpose of control as we define it here, which is to understand and improve the process continuously. This approach is termed plantwide process control and encompasses design, operations, and control. A relatively recent field of research[1,2] it is still a developing field[3] with only a few textbooks or textbook chapters available for the practitioner in the chemical and process industries.[4,5]

This having been said, it is often necessary to enact protective and sometimes compensatory control actions when severe out-of-control variation occurs, such as exemplified in the first eight chapters. These protective actions prevent damage to people, equipment, and process performance while the variation is diagnosed and corrective responses enacted. This is all the more important because corrective responses in complex processes often involve experiments, as demonstrated in the airburn case study (A Nascent Process Disturbance) in chapter 6. In this case, badly airburnt anodes were removed from the pots before they caused serious damage to the pot current distribution. This is a compensatory control action; it doesn't solve or even correct the airburn problem. But nonetheless, it was necessary in a real industrial process while the root cause of the airburn was sought and confirmed.

Definition of Noise and Noise Voltage

Noise is rather imprecisely defined in the industry as the short-term variation in pot voltage, once the variation in amperage is removed. Usually, some calculation of the minimum versus maximum normalized voltage (for current), or pot pseudoresistance, is made over a period, such as five minutes. For example, the min–max calculation over a minute might be averaged over five minutes, with some of those minutes not available for calculation due to beam movement or changes in alumina feed rate.

This calculation is an indicator of the overall stability of the electrical process, in the absence of two major structural influences: ACD (anode current distribution) via beam moves and alumina concentration via feed rate.

Unfortunately, but predictably, there are at least 10 other factors that affect pot voltage in a much less predictable way:

1. AlF3% and temperature
2. Metal long (gravity) waves due to cathode and metal pad horizontal currents and transient forces
3. Metal shorter period waves caused by other anode and cathode current instabilities
4. Anode current distribution changes due to poor alumina distribution beneath the anodes
5. Mis-set anodes that cause periodic low "kicks" in voltage
6. Short circuits to the metal for one or more anodes resulting in a very low voltage for up to 10–20 minutes
7. High voltage creep due to very low alumina concentration, sometimes resulting in anode effects or fast, ghost anode effects
8. Failure of an anode, normally giving a gradual reduction in voltage as temperature of the bath rapidly increases
9. Grounding or spiking of an anode, often giving a "quiet" voltage signal until other related disruptions intervene
10. Low ACD due to low bath height, low bath temperature, or frozen/failed anodes, giving an unpredictable higher frequency voltage variation

The above list shows the ultimate fallacy of relying on the assumption of cause in a control system. In any real process there are far too many unobserved causes for even an expert to ever pick the right one. The cause must be treated initially as unknown.

Therefore, the task of control is really to detect an abnormality or statistically significant change in the process, then diagnose why it has occurred and how to remove the cause. For this purpose, the pot noise is particularly poorly suited. In fact, this signal is heavily filtered and then averaged, so that it is usually resistant to diagnosis in terms of cause, because of destruction of distinctive features and their timing. Therefore, the only possible control action for the automation system is to increase the voltage in order to decrease the noise by increasing ACD. This, at least, allows the alumina feeding strategy to continue operating, because this relies on voltage variation being related predominantly to alumina depletion. If the voltage increase is not successful in reducing the noise, the system will raise an alarm on the pot for action by an operator or pot controller.

Needless to say, the above control action does not address the cause of the noise and it, therefore, returns in many cases when the voltage is returned to normal. This is particularly the case if the noise is not due to any lack of heat input to the bath and cathode (which is addressed by the increase in voltage).

"Seems like there's something going on with the noise, Rob. There's a lot of extra voltage on a lot of pots, due to high noise. However, some are getting a lot more than others, and it doesn't correspond to a particular crew, or with particular anode setting groups, or anything else obvious."

Rob sat down in the empty chair. They were sitting in the potline offices, and the night shift pot controllers for the east end of line 3 were standing with them, spreading a liberal dusting of alumina throughout the room.

Noise. What was that really? Rob hadn't been involved in automation or the definitions of these magical quantities like noise that potline guys liked to talk about.

"What does the noise look like? I mean how does it change the pot voltage, Steve?"

"It's usually just a sort of ripple on the voltage signal if you look at the smoothed voltage we use for feed control, Rob. But, right now, if you look at the raw, amperage-corrected voltage signal, it looks a lot different. Like a big white noise mess, actually. There's some spiky fast stuff on some of these pot signals, mostly downward kicks it seems from my sample of pots so far."

Pot Voltage Noise Characteristics

The plot in Figure 9.1 shows one of the pots in the above potline, over a four-minute period.

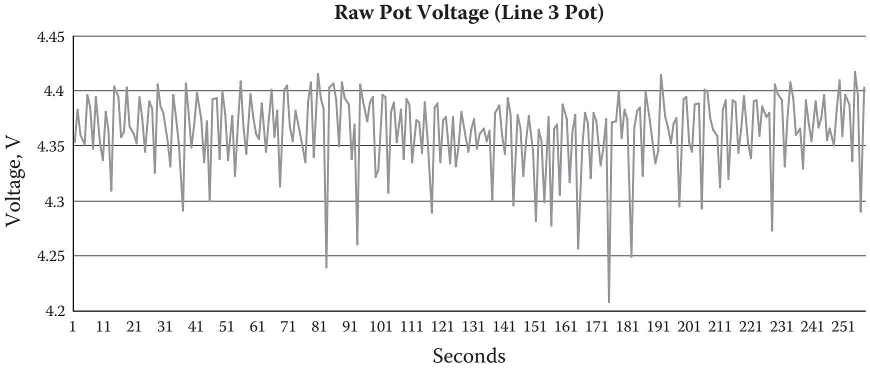


FIGURE 9.1
Raw pot voltage (corrected for amperage variation) for a pot on potline 3 over a four-minute period.

These data are the raw voltage sampled every second and then corrected according to the actual current in each of these intervals. This is the equivalent of a pseudoresistance signal and effectively removes the impact of amperage variation on the voltage.

The variation in voltage shows a general high-frequency component (where high is defined as above 0.5-sec voltage variation). In fact, the high frequency component of the signal is aliased by the 1-sec sampling frequency in the case shown here. When the high frequency component of pot noise exhibits a very high amplitude, 50 to 100 mV for this pot, it is a good indication that a significant amount of electronic conduction of current is happening in the ACD of the pot, as opposed to the current being used for the intended, slower electrochemical reduction of alumina by ions moving through the molten bath to the anode or the cathode. Note that voltage variation due to anode gas bubble release does have a frequency in this range 0.5 to 1.5 Hz as well, however, at much lower voltage amplitudes than observed here.

Electronic conduction means that the normal, slow ionic conduction accompanying alumina reduction in the bath is being overshadowed under some anodes by direct passage of current through carbon and directly into the metal. This is a clear sign of the breakdown of the Hall–Héroult process in the pot.

Also evident in the signal is the occasional "downward kick" of the voltage that is a separate characteristic associated with a mis-set anode, or an anode that is operating much closer to the metal surface than the other anodes. This type of signal occurs in plants where the accuracy of anode setting is poor or where anodes slip through the anode clamps due to poor clamping force.

In Figure 9.2, the same pot is viewed over a longer period of 20 minutes and at the actual sampling frequency of one per second. The data are becoming indecipherable from white noise now, although it is just possible to discern a lower frequency swing in the voltage; it is more visible in the 5 to 10-second bursts of lower voltage readings that reappear in bunches at the bottom of the wave form, at regular intervals.

In fact, this lower frequency signal is noise generated by a periodically circulating wave in the metal pad, but it is occurring at approximately the same frequency as the voltage rise driven by concentration over-voltage increase at the anode due to alumina depletion there. This means that the low frequency noise in the plot can be mistaken for alumina depletion by the control system, which must search for the trigger to end alumina "searching" some 10 to 20 times per day in modern point-fed pots. The termination of alumina searching can be triggered by this low frequency (metal pad driven) noise rather than by alumina depletion itself. This is known as a *"false trigger"* and is quite common in pots where high or intermittent levels of this metal pad-induced noise is present.

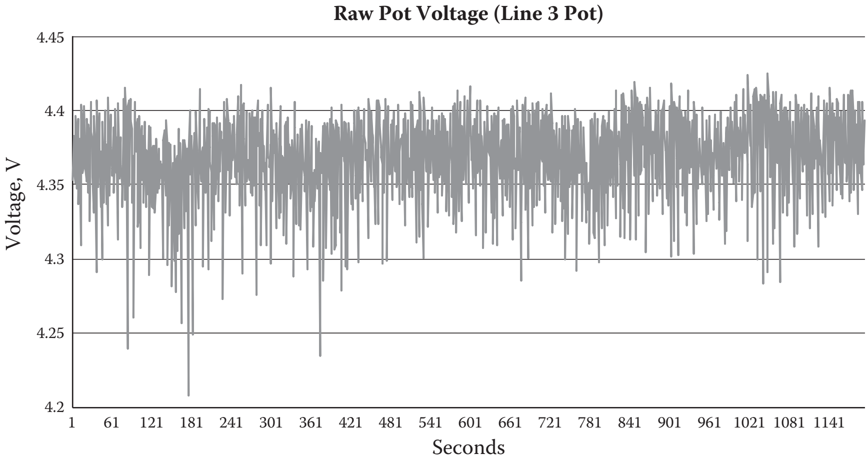


FIGURE 9.2
The same raw voltage signal over a 20-minute period.

Such control errors are guarded against in several ways:

- By suspending alumina feed control if detected noise is too high.
- By low pass filtering of the voltage signal to remove the higher frequency (0.5 Hz and above) noise, so that the true low frequency noise is detected.
- By pot controllers analyzing the voltage by eye to determine if it is triggering due to noise, rather than a monotonic increase in the voltage due to depletion of alumina.

However, where a “mixed” noise signal, as shown above, is encountered, these methods can be problematic because of the poor signal to noise ratio, as demonstrated in the second voltage plot in Figure 9.2. A technical audit of these control systems would conclude that there should be a “soft sensor” for the false trigger problem, because the voltage signal is so critical to alumina feed control. However, the problem has defeated many researchers who have tried to apply models, such as Kalman filtering, and also other electrical filters to the voltage wave form before detection of the alumina-related creep in voltage, which is sought by the control system.

In fact, a completely new and fundamental approach to this problem is required because the problem is not only one of alumina concentration depletion but of poor alumina dissolution and distribution throughout the pot. This is now the subject of a PhD research program at the University of Auckland.

Steve was flashing through screens and pots quicker than the eye, at least Rob's eye, could follow.

"But, that isn't actually what is triggering the noise voltage on most of these pots, Rob. There's something else that is hard to see because of all this other high frequency crap. Looks like a swing in voltage, like a 30-second cycle up and down. A wave."

Steve shook his head, got up and stretched.

"I don't get this control system, Rob. It's so complicated, bells and whistles everywhere. But, what is the thing that is actually starting all these reactions in the system? It's near impossible to tell."

"Okay. So let's look at what we have been doing in the past 12 months, Steve. Maybe there's a clue. Remember, we had anode problems. Well, actually, they were pot problems that affected the anodes and hundreds of extra anodes set every week for at least a month."

Rob turned to the two pot controllers who were just moving toward the door.

"Hold on, guys. Tell me what changed after the anode problems, if anything."

"Well, Rob, that was some time ago, you know. We were on our feet the whole shift pretty much—finding bad blocks, changing them, skimming. You know what it was like. Some of our routine work we had to reprioritize. Thought we'd pick it up later."

Rob was starting to get interested. "What work, Jimmy? What didn't get picked up again?"

"Well, there was one thing that really helped us. We used to check every block after set, to get the setting height right on the mark and find any blocks toe'd in on crust or not square on the beam.

"Stopping that anode setting check gave us an hour and a half every shift. It was the only way we got finished." Jimmy was a career pot controller. He knew what he was saying had a logical flaw.

"We should've started checking the blocks again, Rob, but nothing bad happened after we stopped. And we got busy with getting the new control program going. That got priority."

Rob looked around at Steve.

"We had to put the adaptive feed system in to get the AE (anode effect) frequency down below 0.1 per day. That's one of our KPIs (key performance indicators) for this year. Supposed to be the world benchmark for this technology. So, it took priority over everything else in process control."

"Even routine work?" Rob felt the telltale signs of blood rising. A basal plant operating control (anode setting accuracy) had been removed, and he didn't even know it.

"Okay, explain it to me again, Steve. What does this adaptive feed control system do?"

"Well, it's used quite a lot now in the industry, Rob. The system uses the search time data generated by each pot to gauge whether the alumina concentration on that pot is getting too low or too high. So, for example, if the search times are low, the system increases the feed rate to get more alumina in the bath."

"So, it assumes that the alumina in the bath is low because the normal feed rate is too low, Steve?"

"Yeah, that's it, Rob. So, quite a lot of pots get more alumina, and that stops them having anode effects. Our AEs have decreased almost to 0.1 per pot per day over the three months the system has been across the line."

"And, do we know how much extra alumina has been fed to the potline in that time, Steve?" Rob was not convinced about this idea.

"The computer takes care of it, Rob. Pots that get too much alumina get long searches after a day or so, and that usually leans them out again. Actually, we don't really look at that unless the pots actually cause trouble—like multiple AEs or noise."

Steve was starting to see the possible problems. What if the extra anode-related noise due to poor control of anode setting accuracy had concealed some false triggers on pots that were getting too much alumina? How would they know that searches were being terminated early? And, then, those short searches got processed by the adaptive feed algorithm to give a faster normal feed rate and even more alumina.

"Do you think we might do a little analysis here, Steve? If we are getting false triggers on some of these pots and the guys can't pick them, we might be feeding too much alumina. How about we find out what the real alumina feed increase is across the population of pots over the last three months and look at whether it correlates to the increase in noise.

"And, what have the tappers been saying about sludge? Why didn't we hear anything from these guys? Or maybe we did and didn't listen?"

Steve went to work on it. The pot controllers looked at Rob and both were smiling. Apparently, the computer still had a few things to learn.

Rob walked back to his office, his mind in a state of confusion. This one hour insight into the most important control system in the plant—alumina feed control had shown there was no actual control point on how much alumina was being added to each pot over time. That couldn't be true. Could it?

So, all of the broken control loops around the potlines that they had found—found the hard way—were sitting on the foundation of an automatic control system that *assumed* the reason for variation in the dissolved alumina concentration? Not even that; actually, it just assumed the reason for the variation in pot voltage? And, then, took action using that assumption *without monitoring the effect of the resulting control actions on the alumina balance in the pot?*

There were no real data on how much sludge was in the pots either. In the dim, distant past, the sludge levels had been measured on the dip rod during bath and metal level measurement, but that had stopped some years ago because the data weren't being used. Now the dip was made top down, not cathode up. The previous sludge dip had only been a measure of sludge in the tap hole, anyway, not under the feeders where the sludge built up first. And cathode voltage drop didn't respond sharply to sludge until it had already hardened on the bottom—too late for most pots.

Alumina Feeding and Sludge Formation

Sludge buildup in pots can be tracked quite adequately using the automation system that records every shot of alumina added to each pot over a long period of time. Over a period, such as three to six months, the total amount of alumina fed to any pot can be compared with the metal production and the measured shot weight to confirm the difference between the amount of alumina fed and the amount used to make aluminium (Faraday's law applies, dictating that 1.90 to 1.92 kg of alumina is used up for every kg of aluminum produced).

In fact, the CuSum (cumulative sum) of alumina added to the pot can be calculated against a long-term "average daily alumina usage" for each pot, even without special shot weight or other measurements. The slope of this cumulative sum of the alumina addition will be positive if more alumina is being added daily than the long-term addition rate and negative if less alumina is being added per day.

In Figure 9.3, the CuSum of alumina is computed for pot 87 over a four-month period, along with the bath temperature, XS AlF3%, and AE frequency.

The surprising aspect of this chart is the magnitude of the imbalance in cumulative alumina addition that builds up over a period of more than a month on one pot. In fact, four metric tons more alumina are added

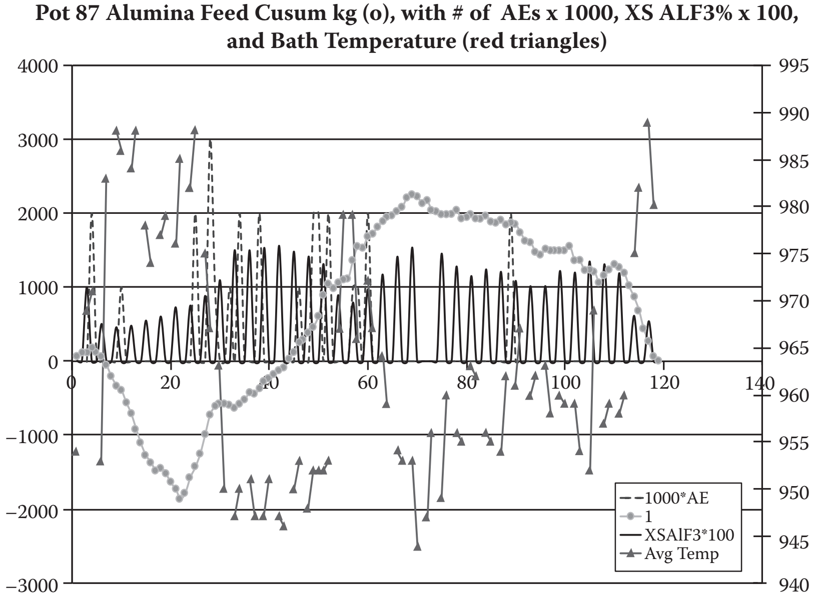


FIGURE 9.3 (See color insert.)
Example of alumina feeding imbalances driving pot heat balance for a point fed 220 kA pot, over a 120-day period.

from days 20 to 65 than can be converted to aluminum in this time, although over the entire period of 120 days, the average addition rate of alumina is achieved, validating the use of the CuSum as a measure of sludge buildup/redissolution. Four metric tons of alumina unfortunately are equivalent to more than eight metric tons of sludge buildup on the cathode of pot 87. This is a massive change in the bath mass balance and results in bath transfers into the pot in the first half of the 120 days and bath transfers out of the pot in the second half of the period as sludge was redissolved again into the bath.

Along with the more than 50% fluctuations in bath volume, large swings in the concentration of aluminum fluoride concentration are also observed, moving between 5% XS AlF3% at the start to 15%, as the rate of sludge formation reached its most rapid around day 40. This is because the sludge itself does not contain much XS AlF3, being composed mainly of cryolite saturated with alumina and undissolved alumina.

The effect of the sludge on the heat generation in the pot is not shown in Figure 9.3. Both noise and voltage additions increased also from about day 40, along with anode adjustments and current distribution problems. The temperature gradually increased on pot 87 over the second half of the period as sludge gradually redissolved in the bath. However, this process always leads to overheating of pots due to the reduced amount of alumina being added per day and the increased voltage noise and actual operating voltage being applied to control it. By day 110, the temperature is spiking above 970°C, and soon after it goes out of control, in the range 980 to 990°C for the last week.

The detailed, longer term effects of the large amount of alumina sludge deposited on the cathode are not known for this pot. However, its cathode voltage drop remained permanently 30 mV higher than the initial value at day 1. It is observed generally that pots subjected to more than one of these "sludge cycles" over periods of months and years develop special cathode deposit problems that are permanent, causing higher noise over their remaining lives. In this respect, pot 87 is not an outlier for sludge buildup. The same types of sludge cycle have been observed on more than 50% of the pots on which the alumina CuSum has been plotted so far, despite differences in feeding technology and type of cathode.

Steve burst into the potroom offices clutching some papers, almost running. Rob opened the door, so it wouldn't get battered down.

"Rob, we got 30% of pots that have been accumulating more than two metric tons of alumina, according to their individual shot weights and their number of shots per shift for at least the past month. Another 25% could have done so, but it's not conclusive; maybe their current efficiency was 98% or more instead."

Rob looked at the data. Steve had plotted a CuSum of the alumina for each pot, and its slope had changed upward in many cases; more than half of the pots on the line showed this change in slope.

"Can we kill the adaptive feed algorithm and return the pots to a fixed feed interval, Steve?" Rob asked it as a question, but Steve knew there was only one right answer.

"Doing it now, Rob. But, that isn't going to stop the false triggers. We still have the anode-related noise due to the anode positioning, and the sludge we put down there is still causing the metal pad swing on the voltage. We have to work the sludge off and get the anode table flat again.

"Get Ford to come in, Steve. We need a plan, and it involves the entire operating team, and especially the pot controllers."

The next three hours were a blur of action. Fast reaction was a strength of his production team. Rob stood back and watched the precision of the logistics and organization as the superintendents led by Ford reinstated the anode setting (Check Each Block) procedure with the pot controllers and with a control this time reported to the superintendent on the number of anodes set high/low that shift.

Over the next few days, the process and production teams together devised and implemented a program of gradual leaning out of the alumina feed, pot section by pot section, rather than all pots together. This made it possible to control pot temperatures on that section, with reduced AlF3 addition and small amounts of extra voltage in some cases.

These were the guys to go into battle with, all right, Rob thought not for the first time. Evidently, it also was not the first time that a potline had sludged up at the plant.

The plan would take two weeks to run through the line, but it could be a full month (one anode rota) before the anode noise was under control again. How much time to clean up the cathodes? That was an unanswered question. Rob could feel another chewing out regarding the pineapple session with the general manager on the way. This extreme pot noise was surely affecting production, although, at the moment, the tap was good, metals pads probably pushed up by the sludge. That would all change as the line warmed up with back-feeding of the sludge into the bath, though.

On the straight at 7.30 p.m., Rob let his mind go back to the day's discovery and the plan he had carefully devised some time ago. There had been a step missing in that plan, he thought now—the purpose of the future control system, relative to the current system. And that step would have helped his team understand where they were headed and why a more complex control system wasn't the way forward. In fact, the step they had to take now would define what the purpose of the future control system was going to be.

Process Control Reformulation: Part 2

The traditional potroom control system has incrementally evolved through many years of inconsistent quality operations and a poor or nonexistent connection between the operations, the closed-loop control functions, and the actual performance of the potline. The result is that

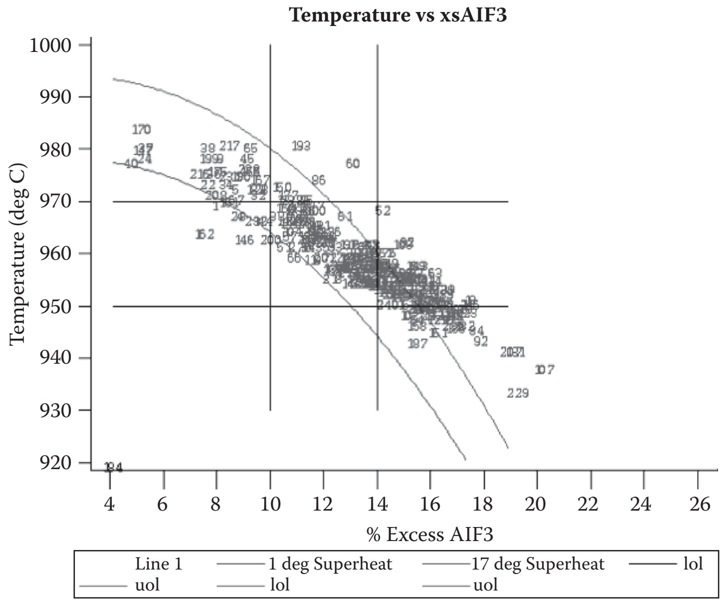


FIGURE 9.4 (See color insert.)
Bath temperature/ALF3% concentration slice of the pot operating window, showing real data from one potroom. In this case, the lines of constant calculated superheat are 1°C and 17°C, but the percentage of pots in this range is still only 55% because the univariate controller responds to the temperature and XS AlF3% variables separately (the control box shown) without consideration of the dependency between them.

at least 40 to 50% of pots remain outside the target operating envelope of temperature/composition/voltage/alumina and anode performance, at any given time and without any concerted control objective to improve this level. An example of this is shown in Figure 9.4 for a temperature/AlF3% slice of this operating envelope where a entire potline is plotted with one data point per pot, and the target zone for temperature and XS AlF3% is identified as well.

Calculated superheat lines are also plotted on the diagram, and this shows the extremes of calculated superheat that many of the pots may be operating at on this day. In this pot technology, the bath superheat that is sustainable is 7 to 13°C, without cold cathode problems on the low superheat side or sidewall and anode cracking problems on the high side.

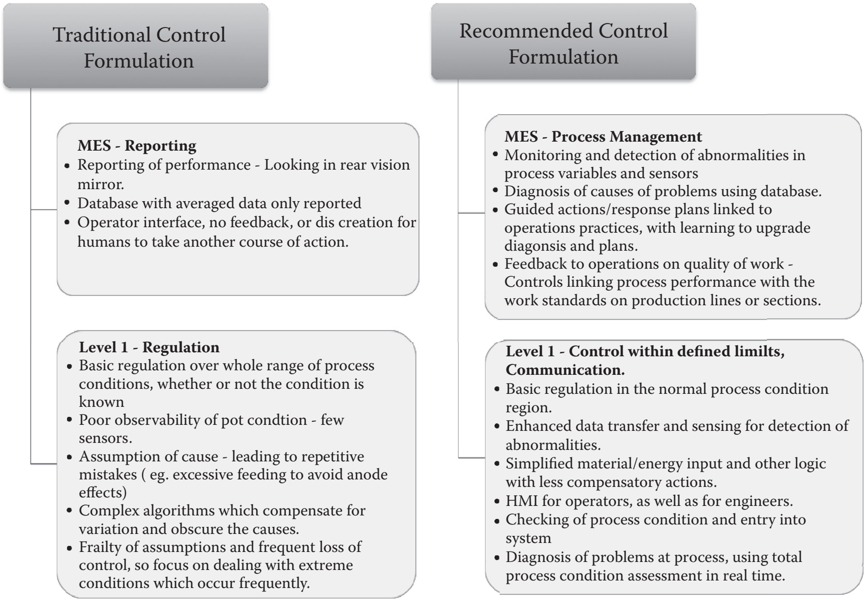
In response to these frequent, extreme pot conditions encountered, more emphasis has been placed at smelters on remediation of sick or abnormal pots, with regulation of these abnormal conditions taking priority over prevention of the conditions. The result is a very complex set of pot control algorithms at level 1, termed by James Reason an "opaque system" in terms of humans being able to understand it or understand how it will respond under any given circumstance.

This is the situation facing the smelter in question here, with many pots having multiple anode effects, high voltage, and low current efficiency. The response of corporate management has been to search for a "silver bullet" control system change in the level 1 feed control module, in order to reduce anode effects. The adaptive feed algorithm is the latest of these "added complexity" pieces of logic. In this case, as in most others, the *assumption of cause* is the first mistake. The assumed cause is that a low underfeed or search time means that not enough alumina has been added and that more should be added. This assumption is false on many occasions because of

- poor alumina addition due to blocked feeder holes or other mechanical problems;
- poor alumina dissolution when it is added to the bath;
- poor distribution or dispersion of the alumina along the pot;
- poor quality of alumina, causing it not to reach the feeder hole or to reach it in limited amounts; and
- extra alumina entering the bath over days as sludge back-feeds or more crust is melted.

All of these processes mean that search times can vary significantly over time. Responding to this variation with an assumed cause is a recipe for loss of control in the overall alumina balance on the pot. Of course, on many pots, it can be successful for most of the time if the above abnormalities are absent. However, the impact on the other pots is so serious that the overall potline distribution becomes increasingly fragile to any shocks, such as alumina quality, power fluctuations, anode variation, or changes in work standards, such as the quality of anode setting, cover dressing, feeder maintenance, bath height and composition, and others.

The real impetus for change in process control in industry now is occurring at the Management Execution System, or supervisory control system level, where it is possible for humans to interact with the data, analyze the variation pot to pot—or production unit to unit in other processes—and find the real causes of variation. This mirrors work done 50 years earlier in the manufacturing industries (W. Edwards Deming, in particular) and has been discussed earlier. Figure 9.5 summarizes the change in control formulation that is occurring gradually in the production industries, including in aluminum production. It is evident that process management and sensing of abnormality will eventually replace the old ideas of reporting and regulation as the central concepts in control. Where it does not, a decline in both production control and the safety of materials processing continues to occur until the plant is either closed or sold. So, it is case of natural selection.



MES - Reporting

- Reporting of performance - Looking in rear vision mirror.
- Database with averaged data only reported
- Operator interface, no feedback, or dis creation for humans to take another course of action.

Level 1 - Regulation

- Basic regulation over whole range of process conditions, whether or not the condition is known
- Poor observability of pot condtion - few sensors.
- Assumption of cause - leading to repetitive mistakes (eg. excessive feeding to avoid anode effects)
- Complex algorithms which compensate for variation and obscure the causes.
- Frailty of assumptions and frequent loss of control, so focus on dealing with extreme conditions which occur frequently.

MES - Process Management

- Monitoring and detection of abnormalities in process variables and sensors
- Diagnosis of causes of problems using database.
- Guided actions/response plans linked to operations practices, with learning to upgrade diagonsis and plans.
- Feedback to operations on quality of work - Controls linking process performance with the work standards on production lines or sections.

Level 1 - Control within defined limilts, Communication.

- Basic regulation in the normal process condition region.
- Enhanced data transfer and sensing for detection of abnormalities.
- Simplified material/energy input and other logic with less compensatory actions.
- HMI for operators, as well as for engineers.
- Checking of process condition and entry into system
- Diagnosis of problems at process, using total process condition assessment in real time.

FIGURE 9.5
Reformulation of the generalized control system at both management execution system (MES) level and at the (level 1) automation system level.

Rob looked up from his desk. It was easy enough to say what was intended in the new control formulation. But how? What management systems were involved in supporting the change?

Systems Involved in the Transition to Scientific Process Management and Control of Production

ORGANIZATIONAL SYSTEMS

The key systems that are required to reformulate control of production are not the control systems themselves. They are the management systems linking people's actions on the production floor with the production process, the design and specification of work, the recognition of that work, and career advancement of the people who do it:

"What is my job?"
"How am I doing?"
"What is my future?"

So the basal systems for control of production at this new level of performance include

- *Integrated Process Management* (and supervisory control) is required to connect the performance and safety of the plant to the critical variables and procedures that determine it (as used in Keith Sinclair's industry benchmark IPMS strategy, for example). The system must have measurement and control plans that specify what will be measured and how/when/by whom, charts that signal a change in the process and can be interrogated and stratified to identify likely causes, and response plans that are enacted to prevent damage to the process, diagnose cause, and correct the variation or remove it from the system, with accountable staff.

- *Standard Operating Procedures* (also called *workplace instructions, current best practices*). This system must be maintainable and incorporate the writing, reviewing, updating, compliance auditing, and training of staff to meet the work standards embedded in the SOPs (standard operating procedures). The biggest mistake globally in SOP management is not connecting the description of work outcomes with the actual measurements of outcomes—the production control points. *Controls on the production process*, if present, can highlight design and compliance issues in the way that the work is actually being done, and this should be continuously fed back to improve the design and understanding of the work—through the SOPs and associated training program. Audits performed in many plants have not identified a single case where the SOP for the work was an accurate description of how the work was now being performed. In addition, it is certain that even routine work, such as anode setting across all of the production units and shifts, is not being performed the same way. Variation in the way work is performed gives rise to widely varying outcomes of tasks, such as mis-set anodes, anodes set on lumps of crust, spiked anodes, etc. If no *control* exists to measure these outcomes on every anode set, there can be no effective identification or feedback about these work variations, and the variation increases.

The underlying problem here is the understanding of the work of production itself. This involves not only *content* but also *sequence, timing, and outcome.* An outcome of a work process has been defined through experiment previously by Taylor et al.[6] in 2010 as the immediate visual, and binary result of the task in real time as it is being undertaken; it is either done correctly and completed or not. But, this type of outcome is seldom specified in SOPs. In fact, the work processes themselves are often not designed to allow such a clear outcome; there are shades of grey, of interpretation. *The design of the work* is, therefore, the place to start in ensuring SOPs are meaningful and can be connected to the control points of the production process. Clarity in work outcomes is a basal requirement for any production system. It provides fluency and integrity in the control process but also in the recognition of the work of staff and contractors.

- *Work performance* recognized on basis of compliance to SOPs, identification of problems in the work design or in the production process, minimizing and reducing damage to processes and harm to people, as well as the potential for these: incident identification and control. If these things are not being measured through an Integrated Process Management System, the recognition of work performance lacks real data and can become "a general pat on the back," which eliminates differentiation between crews or individuals and invalidates feedback for outstanding work.[7] This link extends right down to the level 1 control system where much of the raw data for control of work is collected, or not.
- *Incident* (including control abnormality) investigation. This system must be accessible to the staff at all levels and incorporate a mechanism for review of incidents that is transparent, ideally involving representatives of the whole work force through organizational appointments or committee structures (e.g., safety committees for specific hazard types, such as working at height, enclosed spaces, mobile equipment, rotating machinery, etc.). If these structures are not in place and connected to incident review and investigation, the weight of hundreds of incidents can quickly overwhelm frontline supervision and management in any production plant. After this, the incident system itself becomes suspect because of inaction or subverted to hasten resolution of issues. In one audit of an SAP-based incident and accident system at a smelter, it was found that the root cause of the incident had been discovered in only 5% of the incidents in the system. Further, it was found that hundreds of actions were pending for many months and only a few managers were accountable. If the new work of preempting process and safety failures is not distributed through the entire organization structure, it is evident that this work will probably not take place.
- *Change Control* (for engineering and automation systems): Strict change control is essential for any design, equipment supply, or other system involving the work of people. It also is mandatory for any process change (e.g., The vent pipe on the HTF tank in chapter 2). Of the same importance is the control of automation changes, not just in the potline, but also in Programmable logic controllers (PLCs) that control equipment in all areas of the plant. In particular, the overriding of PLC logic and the operation of equipment in manual or auto/manual modes need to be monitored, recorded (e.g., percentage of time spent in manual for critical equipment items), and investigated because these occurrences are harbingers of other more serious process and safety issues.

- *Safety Observation System.* Systematic daily safety observations are the backbone of any safety system. However, they also form a bridge between the organizational layers and particularly with management. It is rare nowadays to find managers who understand the detail of all of the work of their production floor employees, but daily insights into this work through interaction with employees enriches both staff and managers. In fact, the system would be better called "Safety Observations and Interactions" because the second part of this process is even more important than the first. Training on how to observe in the workplace and how/when to interrupt unsafe acts and give useful feedback about the work of people is needed for all staff, not just management. When this system works effectively, it is possible to extend it to observation of processes that are performance related—to provide a direct feedback on the effectiveness of the work outcomes in terms of the production of the product. This should not be done until the serious safety issues have all been addressed, however.

Organizational Structures

The above systems are dependent on having the organizational power and flexibility to engage a much broader and deeper cohort of the staff and management than is seen in many production organizations, for example:

- *Routine management responses*, which are based on rapid escalation of problems through and especially across the levels of management, most often at facility/superintendent level, where both the detailed knowledge of the process and the equipment and the direct accountability for the people resides. Relationships between operating and maintenance superintendents and between shift crew leaders in the carbon plant and potlines are examples of pivotal communications and problem-solving mechanisms that cannot be replaced by day shift, week day conversations between managers, on subjects about which only the production staff have detailed information.
- *High tempo responses* when a serious signal of instability in process or high workload or other complexity raising situation is recognized, e.g., a failure of control hardware or a software problem. In these situations, the extant, permanent organization that is designed to lead in normal circumstances should give way, at least at the operating level, to one in which individual's specialist expertise takes precedence. This will need to continue until the emergency or critical situation is fully resolved.

- *A Safety Committee Structure* as described earlier, which also cuts across the organizational hierarchy and involves all or most of the key expertise and knowledge in operating and maintenance areas across the plant. Typically each safety committee has responsibility for one category of major safety or process risk, bearing in mind that a major process risk at high temperature or critically dangerous material plants almost always involves a major safety risk; the two risks then become indistinguishable.
- *Emergency response team*, which acts according to preplanned response protocols and usually is based around responses to fire, falls/rescues from height, confined spaces, toxic chemical spills, and serious injuries. The difficulty with this team is infrequent action requirements. Therefore, recruitment, systematic training, emergency response scenarios onsite, external competitions, and management recognition are key to maintaining this capability in any plant.

The above systems and structures connect the entire organization with the production control process. Without this connection, it is not possible to gain long-term advantage from closed-loop control, because the assumed causes become irrelevant within weeks or months, and, thereafter, the system reacts to things that are not happening. In fact, the people on the production floor generally know the possible causes, but the above systems and structures are essential to access this data stream and connect it with the control process.

Rob walked into the general manager's office. In his right hand was a list. It felt good for once to be the guy calling the meeting, rather than being called to it.

For the first time, it was clear that to reform the control system, change was needed at all levels of the organization. In fact, it was even more than that. Change needed to happen with the management behavior before it could occur at the production floor. And circumstances had given Rob the perfect example—corporate management trying to drive through a control system change at the expense of maintaining high-quality anode setting operations in the potroom.

John Simcox sat at his desk, and the seconds mounted after Rob had finished speaking. Rob had learned to watch John's hands. On this day, they were very white and still. A pen was in his right hand. But it was motionless. John looked up.

"We made a mistake, Rob. A management mistake. But, there is starting to be a pattern here. I think this is the fifth time you and I have sat here, after losing control of the plant. So, now I need to break the pattern."

Exercises

1. Considering the exemplar processes given early in this chapter, what are the three general considerations that lead to the definition of an operating and control envelope for an industrial process?
2. What control elements need to be reconsidered in order to achieve such a control envelope? What is the central reason why this change in control formulation is necessary, thinking of the failures in automatic control revealed in this chapter, in particular?
3. What three questions most occupy the minds of people working in an organization? How are the answers to the first two connected to the control of production?

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10

People, Process, and Plant

Sweat beaded on Rob's forehead as he pushed the pole into pot 160, which was still on and off anode effect now for over 20 minutes. He was standing at the duct end where Sam had directed him.

"Okay, Rob, put that pole down into the sludge and stir it up in the corner. The problem's coming from that end; it's sludged up."

It seemed as usual that the operators knew more about the details of the process than most of the engineers and all of the management.

Rob had been walking along line 1 when he saw Sam in trouble trying to terminate a manual anode effect. It kept turning off when a wooden pole was pushed under the anodes at the tap end, then coming back a few seconds later.

The number of anode effects over two minutes was one of the new control points Rob had introduced as part of the new process management system. It was several of the crews themselves who had insisted on it, because it mattered to them. But, interestingly, it was also a measure that responded most quickly to changes in the process. In fact, it had taken a kick up off the chart in the last week, and this anode effect was just one more. And the long anode effect problem had been immediately picked up and analyzed.

There had been a change in the anode setting sequence last month to combat airburn on one exposed side of young anodes because they were next to an anode about to be removed. The change had decreased the time the new anode face was exposed to air, before the next one was set beside it. And that was helping reduce airburn.

However, in several locations, the new anode setting sequence also meant that several new anodes were set around the same feeder hole, and the crust breakers sometimes failed to open that feeder hole, especially on the shift after anode setting. Piles of alumina quickly formed there, and, then shortly after this, a pile of sludge went onto the cathode.

This physical cause had come to light only this week, and only as a result of the long anode effects measure. Because of the rapid detection, the cause had been investigated before there were many pots affected. So far, only three to four pots per line had overheated as a result of the sludge problem, and these had been identified due to their long AEs and were now being cleaned up by the respective pot controllers.

In fact, without Rob's intervention, Steve and the process control team had come up with a hypothesis and a possible solution. They were already testing it on 50 pots on line 2. Anode setting voltage was normally added for only four hours after the setting operation. The theory in the past had been to compensate for the loss of ACD (anode current distribution) due to the new and inoperative anode, to reduce squeezing of the anodes toward the metal pad. It was not clear if that theory had ever been tested.

But, some test measurements each shift on a few pots over the last two days had shown that bath temperature was significantly reduced on the shift after setting because the cooling effect of the new anode was still present in the pot long after the anode setting voltage had been removed. Thus, the test group had been given a smaller setting voltage addition initially, but ramping off over eight hours rather than four hours. So far, there had been 80% fewer nonbreaker events on the test group versus the normal amount on the 50 control pots.

“How many more of these nonbreaker pots do you have, Sam, on this section?”

“This is the last one right now, Rob. But, we’re still finding the odd one or two on this room. Until we can apply the modified setting voltage program, we’re sitting ducks. Still, at least we’re onto the problems quick these days. Things don’t get out of control.”

Sam might have been smiling as he cleared away the unused anode poles and put the pot back on normal control.

Walking back up the line, Rob could almost bring himself to smile as well. Yes, there were signs of improvement here and there for sure. But, it was hard to be really sure. Just then Rob’s phone started to vibrate in his pocket, and he moved quickly off the line. Due to popular demand, the contact system had moved on now so that Rob had a special phone on which he could be reached if the matter was urgent.

“Rob, it’s Ford here. Everything’s okay, no one hurt. But, we have a situation. Line 3 is off-load because of a pot tapout, and it’s damaged one of the cutout wedge gaps on the pot bus bar. We’re trying to locate the bypass bus, but it’s not in its storage bay. So, we might be off-load for a while.”

“Okay, I’m on the way, Ford.” Rob put his smile away for another day and turned into center bay toward line 3.

There were actually three bypass bus sections, it turned out later. Any one of the sections could be used for any line. They were seldom used, and only one of the potlines had, in the team’s collective memory, ever put one into service to cut out a pot, which had damaged wedge gaps. That was more than three years ago.

Until today.

“I’ve got four guys off lines 1 and 2 running around site on forklifts and pickups looking for the bypass section, Rob. We need to find it quick, wherever the hell it is. Line 3 loses bath real fast when it’s off load. Less anode cover. We’ve been off for 40 minutes already.” Ford was talking into the RT at the same time and walking back toward the pot that had tapped out.

That was the problem with tap outs. You never knew exactly what was going to happen when molten metal at 950°C came out of the potshell. In this case, it had gone in a rush straight through the perimeter joint and come out of two collector bars fast on the upstream side of the pot, where the wedge gaps between the risers and cathode ring bus were located. Rob looked at the damaged ring bus with Ford. One of the wedge gaps was almost gone completely, and the next one probably wasn't functional either because the bus had warped badly sideways due to heat. This was going to be difficult to fix. Three new ring bus leaves and more off-loads for welding on the line, and all because they hadn't been managing the pots at risk of failure for years. There were still 21 out there, across all the lines.

The search for the bypass bus sections had focused around the storage bays at the ends of the potline, but, in fact, the bypass sections hadn't been stored there for over two years. This fact was revealed casually by the general services superintendent who had been potline maintenance foreman some years back.

"Yeah, when you need it, you need it, eh, Rob." Paul Malony had said with a smile, while he got on the RT and had the solitary remaining bypass piece brought up from the basement storage area where it had been resting quietly, waiting not to be found.

"Still, it's good to have a place for everything, and everything in its place."

Not for the first time, Rob breathed in and out deeply. They had been offload 1 hour and 25 minutes.

"Anything else you'd like to tell us, Paul? Before you go, I mean." Rob measured out the last five words so they weren't lost on Paul.

"Ah, no, Rob. Call me any time." Paul quickened his pace as he left the potroom offices.

The Lack of Institutional Memory in Companies

Mistakes and accidents occur because people do not use the knowledge that is available. To quote Ecclesiastes 1:9 (NIV), "What has been will be again, what has been done will be done again; there is nothing new under the sun."

Companies often have very limited institutional memory. Kletz[1] wrote, "Organizations do not learn from the past or, rather, individuals learn, but they leave the organization, taking their knowledge with them." This factor may be even more at play in maintenance situations than operational ones, because many equipment failures occur only once in two or five years. These events are often critical for plant security, but the people who last dealt with them are no longer in the company or most likely have moved elsewhere in the organization. While *explicit knowledge* is often documented in the form of standard procedures, company history, or such like, memory-resident *tacit knowledge* becomes lost.[2] This is certainly a factor in the lost bypass bus section episode just experienced in the potroom.

Kletz[1] titled the second chapter of his book, "Organizations have no memory," in which he wrote: "After 10 years, most of the staff on a plant have changed. No one can remember why equipment was installed or procedures introduced, and someone keen to cut costs or improve efficiency, both very desirable things to do, asks: 'Why are we following this time-consuming procedure?' or 'Why are we using this unnecessary equipment?' No one can remember, and the procedures may be abandoned or the equipment removed."

The following lines from Kransdorff[3] are very incisive:

- Many companies reproduce their blunders on a regular basis.
- Many companies continually reinvent solutions.
- By sacking long-serving managers every time they [the bank] made a business mistake, they wiped out the organizational memory and increased the chances of making further mistakes.

It is most important that we learn from the past, disseminate the knowledge, analyze, and improve on it, and then apply it appropriately. Marcus the Elder asserted that "wise men profited more by fools, than fools by wise men for that wise men avoided the faults of fools, but that fools would not imitate the good examples of wise men." (*Life of Marcus Cato* by Plutarch (46–120 CE), see Dryden[4].)

Clearly systems to retain critical information over long periods are required, and these cannot be dependent on a few individuals only.

Later, after the debrief, Rob sat alone in his meeting room and thought about the day. It wasn't all bad. Line 3 was back and becoming more stable by the hour. No obvious damage done. The crews were making big strides in the direction of process stability. In fact, they were questioning changes now, asking why they were needed and how they would affect the key control points on the potroom process flow chart.

However, there were big blind spots out there. What about the maintenance of the plant and its critical equipment? The "near death experience" today had rammed that message home. How did three bypass bus sections get reduced down to only one piece, stored where no one in production knew where it was? At least some of this problem was due to a lack of operational orderliness and readiness in the workplace. There was no longer an appropriate place for each of the essential equipment items. And these items were not stored in their own space either. Other things cluttered the space and confused the purpose of the essential equipment. In fact, even the condition of equipment was in doubt. You couldn't tell the condition because the equipment wasn't clean. And no one was responsible for monitoring this. Thus, over the longer term, it was no surprise that it all became too hard. No one could keep all the balls in the air without the discipline of the entire organization. There were probably more than 300 such equipment items across just the potrooms.

5S in the Workplace

The five steps for creating an ordered workplace (the interior of the wheel) are shown in Figure 10.1. 5S (sort, set in order, shine, standardize, sustain) opens the way for other far reaching improvements through exposing waste and problems with equipment and processes. These opportunities as shown around the perimeter of the wheel in Figure 10.1.

The implementation of these 5 pillars starts with "sort" or organization on the top left, then "set in order" or orderliness as shown on the top right. These are closely followed by shine, standardize, and sustain. However, there is no question that the first two steps are the hardest. Once these are achieved and the workforce has control of their own workplace, pride in the daily achievement of order and a high-quality environment drives further improvement, and the cyclic 5S process can become self-sustaining as long as the daily achievements are recognized by management.

"Ford, starting next week, I want to have sessions with the crew leaders about how we manage the potroom equipment. We'll do them two crews at a time, in the training room, just after shift change."

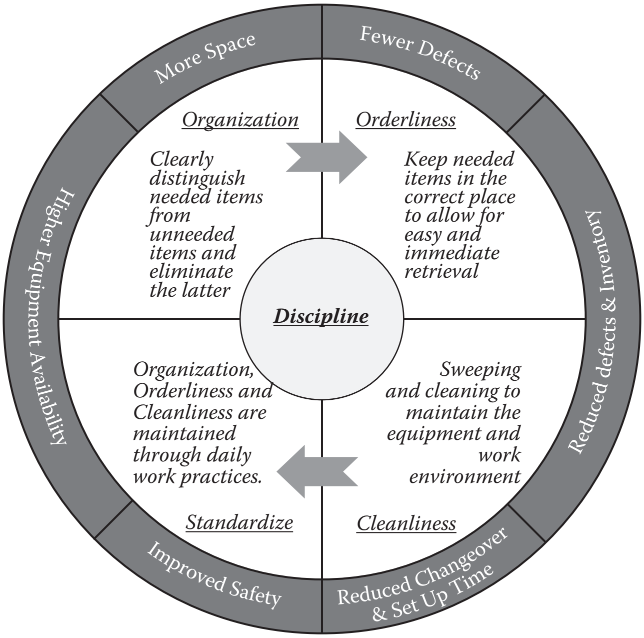


FIGURE 10.1
5S steps for creating an ordered workplace. (Adapted from The five pillars. In *5S for operators: Five pillars of the visual workplace*, p. 13. Portland, OR: The Productivity Press Development Team. Based on the book by Hiroyuki Hirano, 1996.)

"Okay, I'll organize it, Rob. I reckon things might get a little hot in these sessions, though. You know how many breakdowns we've been getting with the cranes this last month. And the pot maintenance is just about as bad. Sometimes you'd be hard pressed to find a maintenance guy on shift out there to fix a breaker, with the cut backs." Ford could always be counted on to give Rob the other side of the story.

Just as well to hear it before the crew leader sessions, Rob thought. But, it was time production took some more responsibility for maintenance jobs, anyway.

Yes, it was more than achieving a sense of order, Rob thought. That was only the start of the maintenance process. What happened to the condition of routine production equipment over time, like the pot tending machines, and the host of machines in the carbon plant? These machines were used every single day. Did they degrade? And how fast?

Rob looked at the now much-annotated potroom flow chart on the wall (see chapter 7). Opposite *Pot Equipment Maintenance* there was the optimistic control point: *% Planned Maintenance completed to Plan*.

The data for this measure weren't plotted as of yet, but there were some postings last month from the various maintenance teams. None was over 40%, and the green carbon plant maintenance was running in breakdown mode pretty well continuously—nothing got completed to plan. Why was it Rob had never seen that data? It was on the wall now, but no one in the operations team was talking about it. It was as if maintenance was invisible, unrecognized.

The next day, there were five maintenance superintendents from across the plant sitting around Rob's meeting table. Rob had met each superintendent before, but this was the first time they were sitting around the same table to work on the business. That fact was not lost on anyone. There was a silence among the five, not broken by Rob's entry into the room. Looking around the table, there were stony faces, darkened by oil or lubricant, or carbon or bath, or more likely a mixture of all of those.

The carbon maintenance superintendent, Joe Black, broke the silence.

"Rob, I've got green carbon down for the third time today. We're making 7% green scrap, and the green stack is under 1,000 anodes. Can we keep this short?"

Behind the carbon dust and grease, Joe's eyes were tired and bloodshot. The pressure of production didn't only apply to the operations teams, Rob realized.

Green Carbon Case Study: How to Develop Effective Planned Maintenance

Green carbon reliability has a significant impact on safety within the carbon plant, anode quality and performance, and costs. Breakdowns in the paste train (chapter 4, top section of the smelter flowchart in Figure 4.1) expose maintenance and operating personnel to coal tar pitch. Frequent start-ups (due to shut downs) in the plant increase anode scrap rates due to cold equipment and produce marginal quality anodes that may not have acceptable performance in the potlines. High levels of breakdowns require higher numbers of people on shift maintenance crews. Higher green anode stock levels are then required to ensure continued supply to the anode baking furnace. In fact, all smelter targets (safety, environment, anode throughput and quality, work in process (WIP), costs, and value-added products) are profoundly affected by green carbon plant reliability. Inevitably, not all poorer quality green anodes are scrapped if frequent breakdowns occur. Therefore, problem anodes penetrate into the potroom, where they cause many individual pot operating problems through cracking and poor anode current distribution. Green carbon problems, therefore, effect the competitiveness of the smelter itself.

Appropriate outcome measures of the reliability of the green carbon plant include

- Number of breakdowns
- Green scrap metric tons per shift
- Productivity
- Anodes/day
- Anode-forming stops per day
- Average runtime
- MTTF/MTTR (mean time to failure, mean time to repair)

However, the driver for achieving better results in these outcomes is actually about diagnosis of the causes of failures. The paste train has no significant hold up of material, from the ball mill circuit right through to the anode-forming step itself. Therefore, any fault in this train of equipment will stop anode forming and cause a restart of the entire plant to be necessary with the attendant quality and scrap problems.

Attempting to drive diagnosis of faults when there are frequent critical equipment failures is an almost impossible task, because of the clear urgency to resume production. Thus, the diagnosis process must occur *at times when there are few equipment failures.* This is such an obvious conclusion that it is overlooked in the management of many maintenance systems. An absence of breakdowns should be accompanied by the maximum activity in condition monitoring, planning of maintenance tasks, checking and procurement of critical spares, analysis of component failure frequencies and modes, and measurement of the success of planned maintenance periods through discussion with the operators of the plant (including hand over to maintenance teams, and hand back to operations teams). All of this work needs to be planned and driven on the day shift.

The key measure that can help drive planning in maintenance is the *% planned maintenance performed to plan*. Adoption of this measure requires management at the plant to give a commitment to the maintenance teams and receive one in return. Effectively, there must be planning first and results later, and not the other way around. In other words, the management must invest resources in an activity (maintenance) that will have no tangible outcome for some months—a planning process for each equipment item and system. If this is not done, there can be no effective measurement of work done against the plan and no improvement of the plan, either, according to maintenance and operating team feedback and new information obtained from condition monitoring of the equipment itself.

Additionally, there must be adherence by the operations teams to the preventive maintenance windows scheduled, despite production or maintenance difficulties. Extra maintenance and operating staff will be required on day shift to initiate this more structured way of working on equipment—especially maintenance planners—in order to break the cycle of "breakdown and patch up," which is common in many continuous production plants.

This is the commitment of management to the maintenance teams. The commitment of the maintenance teams is to use this investment by the management as a *circuit breaker intervention* to achieve different results and to measure and improve the result over time.

Many maintenance systems have been devised to speed the above process. None of these are successful unless the above commitment by management is made first. The start of the new equipment failure diagnosis process also requires an assessment of the leverage of improved maintenance and a rigorous cause and effect analysis method to ensure that the highest impact is gained from the available, frontline maintainers who have to identify and replace defective or failing components during the preventive maintenance windows.

In Figure 10.2, the train of three main processes in green carbon (aggregate crush and size, weight heat and mix paste, and form and cool green anodes) can be examined. The recycle circuit for anode butts and the recipe (butts%) for the aggregate demand a steady production of green anodes in order to maintain the final baked and rodded anode quality for the potroom. With interrupted green anode production runs, the green scrap increases quickly, and these scrapped anodes do not mean that the rest of the production is unaffected by the temperature fluctuations of the mixing and forming train. In fact, the entire anode production in "transport to potroom" is certain to have a wider variation in baked anode density and possibly more internal cracks originating in the mixing and forming processes as well.

With poor reliability, production of acceptable green anodes per day is substantially reduced by breakdowns and it is likely that green anode stocks will dwindle to near the minimum level required for any planned

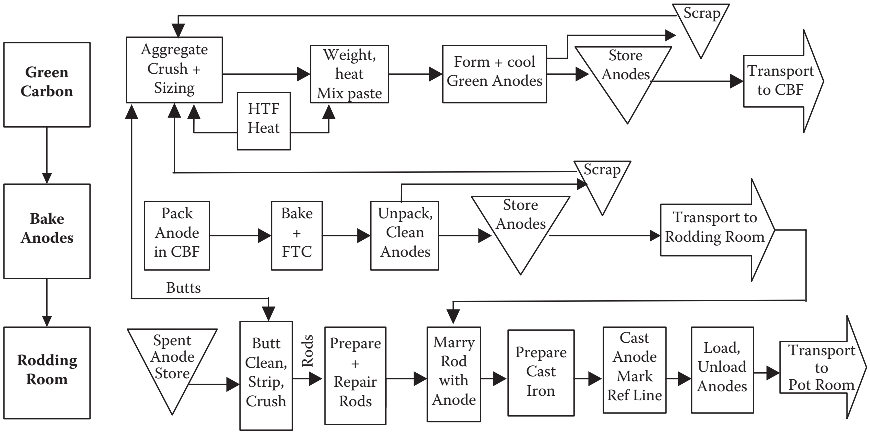


FIGURE 10.2
Green carbon process flow abstracted from chapter 4, Figure 4.2, showing processes impacted by interruptions in green anode, green scrap flows.

TABLE 10.1
Example of Actual Impact of Problems in Green Carbon Reliability in One Smelter

Subprocess	Value Loss Mechanism
Weigh, Heat, Mix Paste	Root cause still present → Rework later Breakdowns cause pitch exposure, injury
Store Green Anodes	Require more green anode WIP to cover breakdown periods
Form and Cool Green Anodes	Variation in anode height increases (temp), leading to higher variation in green anode density Some anodes have poor mixing or compaction → internal cracks (not detected or rejected)
Green Scrap	Breakdowns cause large increases in green scrap
Bake Anodes	Increase in anode cracking Increase in anode airburn
Anode Consumption	Anode cracking in many pots Unscheduled anode changes, hot pots Anode current distribution disturbed → Power consumption, CE affected.

maintenance window. At this point, the plant is in a critical state because planned maintenance can quickly become impossible to achieve. Plants that reach this condition very often have to purchase thousands of baked anodes on short lead times and at high prices in order to create time to work on their green carbon plants.

Value loss in each part of the process in Figure 10.2 is quantified in Table 10.1.

In this table, the effect of green carbon maintenance problems is seen to be pervasive throughout the whole production process. The trigger for potline problems in many cases is internal flaws in a proportion of anodes, initiated in the anode former or due to poor mixing. These flaws are difficult to detect in the green carbon plant, but, in the pots, they can result in a high rate of anode cracking, some of which may be horizontal anode cracking, which has devastating results, such as the bottom half of new anodes being left frozen into pots and unable to be removed. In general, the disruption to potline operations from anode cracking is the most severe consequence of any potroom disruption other than complete loss of electrical power for an indefinite period.

The key question, therefore, is what drives green carbon reliability? Green carbon consists of a production stream of equipment consisting of

- aggregate preparation;
- aggregate proportioning;
- preheating;
- mixing;
- anode formers;
- power and free conveyor, the formed green anode conveyer, which must take the anodes to the green stack, and the butts conveyer leading to the cleaning, stripping, and crushing of the anode butts, which then go into the aggregate preparation operation above; and
- anode conveyors and stacking cranes in the green anode storage area. A breakdown stops the P&F (Power and Free) conveyor, so any breakdown effectively stops this stream.

The base data on failures in the above equipment are maintenance work requests generally entered into an Enterprise Resource Procurement (ERP) system of some kind, and associated costs for these requests can be formed into a Pareto of the above categories. This inevitably leads to two to three of the above items accounting for 80% of the anode forming stops, as in the example in Figure 10.3.

In this case, the data show that the forming process itself, consisting of the preheater, mixer, and former, dominate the breakdowns, although the P&F conveyor system also features.

Combining the direct and indirect leverage associated with reducing stops in anode forming listed in Table 10.1, there is a solid argument for tackling reliability in the forming process before all other parts of the process. Based on additional work request data, crushing, including the butt stripper, would be a likely second candidate for a reliability campaign.

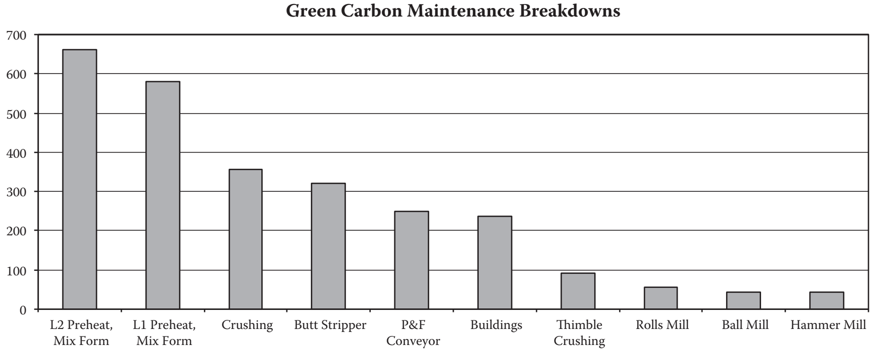


FIGURE 10.3
Pareto chart of the maintenance frequency for the main areas of a green carbon plant.

Cause/effect analysis of the former stops was conducted next and yielded a number of general and then more detailed causes. These are arranged on a cause and effect diagram, such as that in Figure 10.4, with the "effect" connected to causes to the right of it. Asking the question: What is this caused by? allows the more detailed root causes to be exposed by the trades people and operators. Behind most of the "equipment conditions" identified in the diagram here, there are actions that either can be taken, or have not been taken, in the maintenance or operating practices. These are the opportunities for reducing or eliminating causes of anode forming stops.

The results in Figure 10.4 were obtained through targeted analysis of these breakdown areas.

Over a period of six months, a campaign was run to address these causes through planned maintenance, along with targeted upgrading of operator and maintainer procedures. Over an 18-month period, total former stops were reduced from 60 per month to approximately 10, and this gain was sustained over time.

Detection and diagnosis of problems are a databased activity. Engineers and maintenance staff were needed to accomplish this work using the above methodology. However, the detailed causes were mostly identified by maintainers and operators.

Once the causes had been identified, the methods for solving the problems and physically removing the causes depended implicitly on the knowledge and experience of the maintenance and operating staff in the plant. To access this knowledge and experience required a structured ideas generation process, as discussed below.

The key to successful ideas generation is the creation of a positive energy within a group of experienced trades people and operators, many or all of whom may be despondent about the condition of their

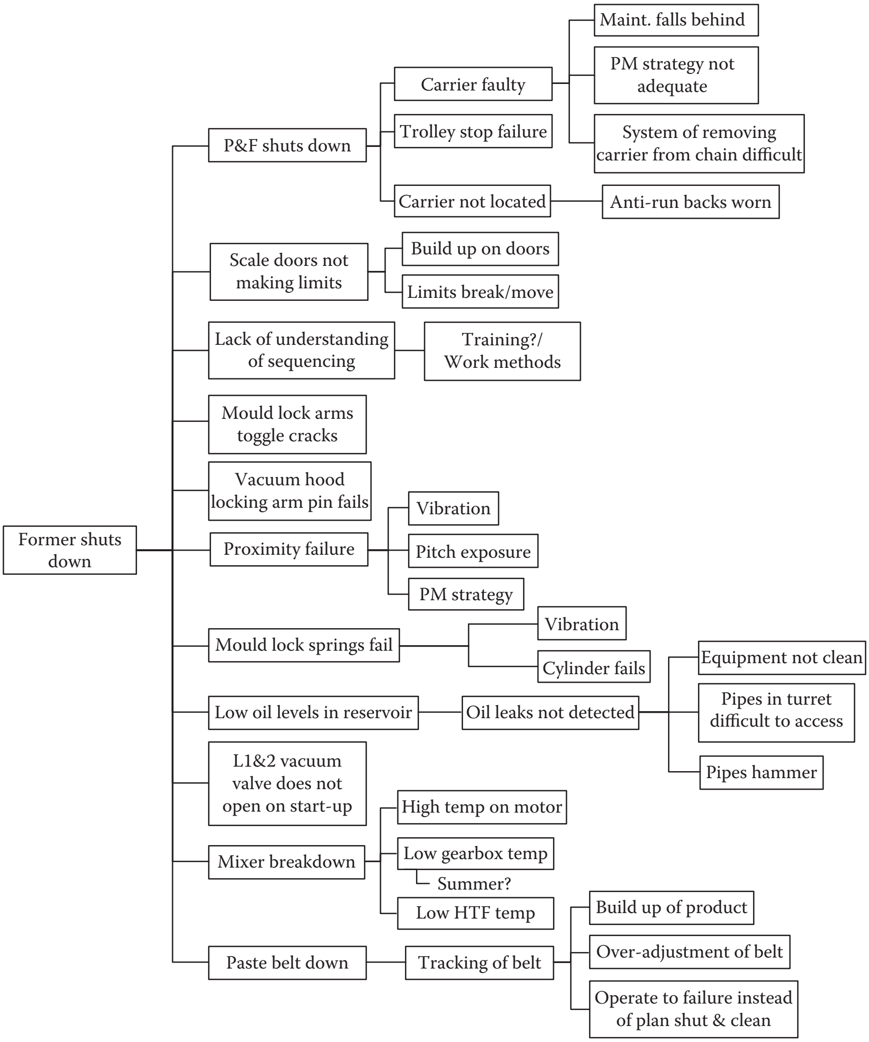


FIGURE 10.4
Cause and effect analysis for anode forming stops from a whiteboard brainstorming session at a smelter.

plant as well as physically tired and stressed by the constant breakdown pressures. Their initial contributions in a group session are likely to be "issues" or complaints to let off steam. These issues have value but need to be converted into constructive ideas in real time during the session, in order to produce a positive environment giving sufficient constructive contributions for a positive outcome.

This technique is exemplified in Table 10.2.

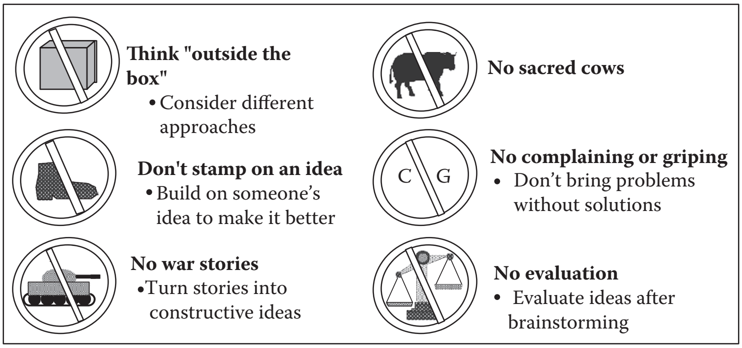
TABLE 10.2

Ideas, Not Issues

An Issue is a Problem Somebody has with the Way Things are.
To Contribute to the Idea Generation Process, it is Necessary to Convert Issues into Ideas.
Some Examples of How to Convert an Issue into an Idea Include:

	Issue/Problem	Idea/Solution	Benefit/Savings
e.g., 1	In maintenance, we spend too much time working with the maintenance system.	We could eliminate tasks A and B that exist only to collect data that are not analyzed.	People's time could be used on maintenance tasks for which we currently employ contractors.
e.g., 2	Cleaning this machine is messy and time consuming.	Provide fit-for-purpose cleaning gear.	Eliminate environmental violations from this task and reduce time taken in cleaning.

Establish Ground Rules for Brainstorming Sessions



Think "outside the box"
- Consider different approaches

No sacred cows

Don't stamp on an idea
- Build on someone's idea to make it better

No complaining or griping
- Don't bring problems without solutions

No war stories
- Turn stories into constructive ideas

No evaluation
- Evaluate ideas after brainstorming

Rob walked out of the plant with Joe Black. They had been going through the planned maintenance tasks in green carbon, and how they could or, in some cases, could not complete them to schedule. There was a lot of work now and a six-month block of maintenance planning to be done. This would require some experienced mechanical trades people to be brought off shift, money to be spent on critical spares and redesign of defective components and a rewrite of both operating and maintenance procedures. In addition, the operating superintendents would not be able to cancel planned preventive maintenance in the future.

However, all of these items were only work. They weren't impossible. And now there was a plan to which both men were committed. Joe had committed to measure and reach a planned maintenance completion rate of 80% as a starting point for the new way of working. Once the causes of green carbon breakdowns were clearer, target reductions in breakdowns also would be established for 6 and 12 months time. The measurement of preventive maintenance effectiveness would begin immediately, and would be boosted by new maintenance plans for each key equipment system as soon as these could be established.

The time was 7.30 p.m., and the night shift was making another restart of the green carbon circuit. Rob and Joe were at the gate.

"That's the first time I've heard we are important, Rob. At least for a few years anyway. There aren't any easy solutions here, you know that. Planning and solving problems takes time, production time. Are you up for that? It's gonna fire up every boss from here to head office."

Rob smiled. "Maybe they need to be fired up, Joe? If we don't get the plant operating stably, there are worse things that can happen."

"Yeah, also ending with the word 'Fired' I think, Rob." Now it was Joe's turn to smile.

Exercises

1. Is the immediate cause of an anode effect a low alumina concentration across the entire pot, or low alumina concentration under individual anodes? What does this mean for the reduction in anode effects? What is the effect of sludge on alumina concentration across the pot?
2. What are the five steps to getting your workplace in order?
3. For maintenance processes, what are the triggers for action that an individual maintainer or operator would use to indicate that a maintenance response is required? Which of the five steps above need to be in place for these triggers to be observable?

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11

Better Decisions for Control

Rob sat back and looked at the control charts. They showed the day-to-day variation in all the key control points for the carbon plant and the potroom. And now that included maintenance. The surprising thought was that it had only been nine months since his plan had first been formulated. Now there were process owners for each of these control points: operators, maintainers, pot controllers, superintendents. Monitoring wasn't dependent on him, or on the IT department, or on other people not connected with producing the product. The signals in the charts were reported, investigated, and responded to by the process owners, without managers like Rob having to find out something by accident and ask what was happening. Of course, these process owners still needed help from Steve, the process superintendent, and his team once they did identify a trend or a spike or other pattern in one of the charts.

And there were still a lot of charts out of control statistically. Each of these had plans for how to get them stable, however, and they were reported on each week, with a chance to drill down and understand whether the root causes were being addressed or not. This weekly review was acting like an anvil on which each process was tested and honed, based not only on the control point but also on the outcome or performance measures linked to it. Maybe, Rob thought, they could go to a biweekly process review after the monitoring and actioning of the charts got to be second nature.

A good example of the review was the periodic heat balance review, which was run by each potline control engineer for their potline. The review already took place every two weeks, with each and every pot in the line being captured in a single page of run charts showing all of the key control points and their target values or allowable ranges over the previous three months. Some pots got a clean bill of health if they were stable and producing well, with a periodic decision to incrementally reduce metal height and pot voltage (even 10–20 mV a month made a big difference here in energy consumption). Other pots were unstable in either voltage noise, bath height, temperature, AEs or had other problems, such as anode performance or yellow flames and sludge. The review served as a check for these pots on whether the day-to-day potline control practices were effective, whether the problems were being solved or not. So, the review was both a feedback loop (a control on the effectiveness of potline routine operations) as well as a method for continuously reducing power consumption and disruptions to efficiency, pot by pot.

Rob smiled at the thought of how it had come about. Walking down the line to his office one day he had seen Ford and Steve looking in each pot together, as they came up toward the end of the line from center bay. They seemed to be discussing something each time they closed a pot door.

"What are you guys up to? If it isn't top secret, that is."

"Just getting Steve to help me out on my patented potline management routine, Rob." Ford grinned. "We're lowering these pots bit by bit over time if they look like they can stand a lower ACD (anode cathode distance). It's a bit of an art, really."

Rob was instantly impressed. "That's exactly what we need to do, Ford. Great idea." Then it occurred to him. "Just before the ink is dry on the patent, though, can I ask what data you are using to work out whether you can take a pot down in voltage?"

"Ah, now you're getting to the top secret bit, Rob." A fair bit of laughing—dry humor. Secrets were not allowed any more in Rob's potroom.

"Just pretend I'm your patent attorney, Ford. And you have to convince me, okay?"

"Okay, in that case we'd better save the rest of the questions, Rob. We're sort of just winging it at the moment. Ford can tell pretty much if the pot is making metal." Steve was a bit apologetic.

"Lazy yellow flame at the end of the pots is a red flag here, Rob. Corner anodes are farther down toward the sludge. So, they react to cathode problems or low ACD first," Ford said in clarification.

Not for the first time, Rob marveled at the deep knowledge inside Ford's head. He just knew it. From experience. Worth bottling, if you could. And maybe you could.

"Okay, that's a good start, guys, but I think you need to combine your eyeball with the key pot control points for the pot. We have them, right? So, where are they? Or aren't they important after all?" Rob challenged. In fact, there was another strength in what Ford and Steve were doing because they were looking at the physical condition of the pots, which included feeders that were not breaking, anodes not set straight, problematic cathode connections, blocked alumina or AlF3 hoppers, or other things like the voltage interface that might need fixing. A fair proportion of pot heat balance problems started right there with physical abnormalities and with physical observations of the electrolysis under important anodes, such as the flame color/type. That was experience gathered from anodes and pots that had had problems over many years. However, not too many people knew it. So, what Ford was doing was creating a system that used and passed on that knowledge. He had made it explicit, rather than just a nod and a wink between old potroom operators.

Periodic Heat Balance Review

An example of Periodic Heat Balance Review data is shown below in Figure 11.1 for a pot in a modern prebake potline. The data here encompass the routinely measurable heat balance variables in this smelter that

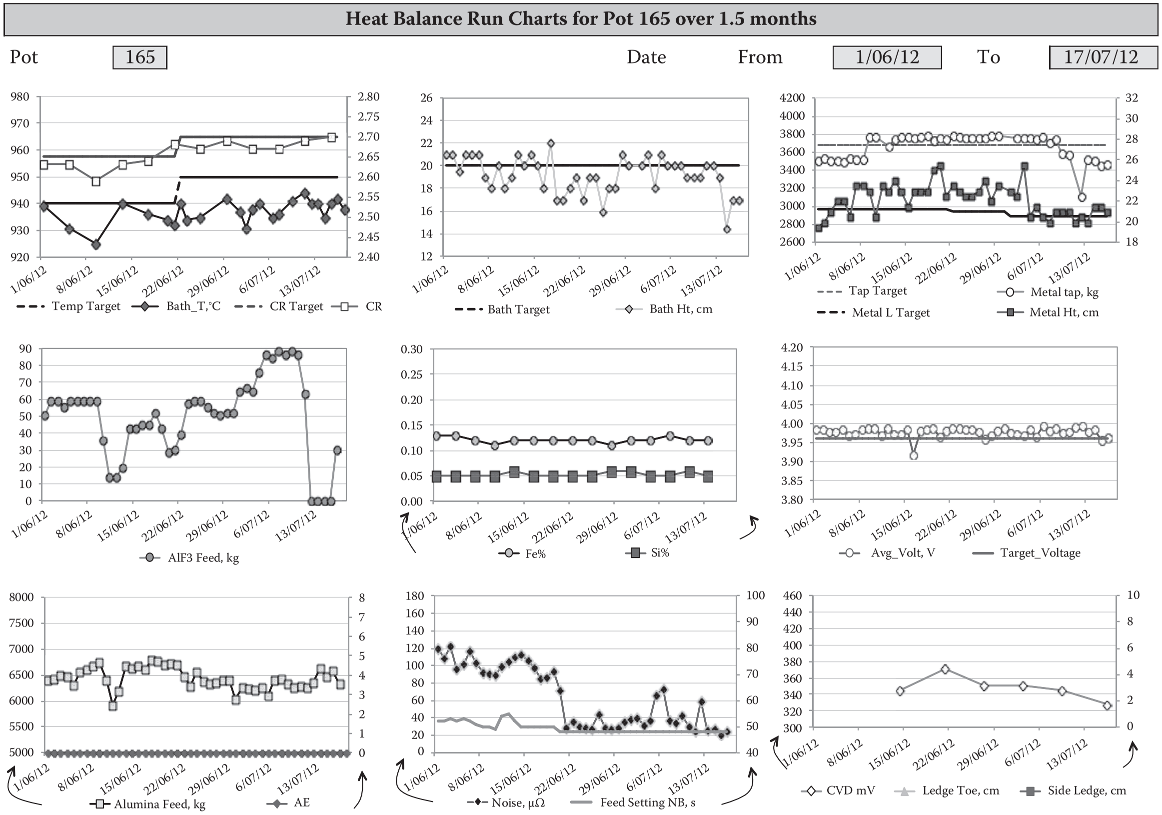

FIGURE 11.1 (See color insert.)
Periodic Heat Balance Review charts for pot 165.

influence the current distribution, energy consumption, and the electrolysis efficiency for the pot. Some new measurements, such as

- Liquidus temperature (e.g., Heraeus cryotherm probe or Alcoa Star probe)
- Duct gas temperature and fume extraction rate
- Anode current distribution across the pot
- Cathode current distribution
- Alumina concentration

are important and are gradually becoming available routinely, as continuous sensing technology and data transmission in potlines improve. Most of these sensors are now available for diagnostic, non-routine use in the potline environment. However, the data shown in Figure 11.1, if viewed over a period of time, are actually sufficient to draw key conclusions about the heat balance, and, in particular, the direction in which the heat balance needs to be adjusted to improve the health of the pot process. Any mistakes made in the decisions reached about a pot are evident two weeks later and increase the learning about the process, as long as the review is undertaken systematically and changes to pot targets are not made in between the two week heat balance periods in which the pot must be allowed to reach a new overall heat balance. This two week period is chosen because it takes 1-2 weeks for the heat balance of a large, modern pot to reach equilibrium after an adjustment. This prevents over-adjustment of an essentially slow thermal process.

Some physical observations concerning mechanical and electrical integrity of the pot may also be added to the charts in Figure 11.1, preferably before the review takes place. For pot 165 in Figure 11.1, the following are the review conclusions; these should take a maximum of 10 minutes to reach and document for each pot.

Observations and decisions made in this case included

1. Low bath level is a problem on pot 165 and not for the first time. In this case, repeated low bath level is linked to removal of carbon dust (and bath) at anode setting that is a necessary procedure when pots have heavy dusting (continuous coverage across the anode hole after anode butt removal) because of the negative impact of setting anodes on carbon dust that collects on the surface of the bath (physical observation by operators of bath and dust removal during anode setting on pot 165). Bath addition in the tap hole each day is prescribed as a sustainable solution to the problem, along with observation of the carbon dust levels and diagnosis of the cause (action next week).
2. Voltage noise and cathode voltage drop (CVD) are both improving as a gradual improvement in bath temperature through increase in the molar cryolite ratio (CR). No action.

3. Given the low bath level and steady temperature relative to the CR increase, there is a high probability of reducing bath superheat. Therefore, reduction in pot voltage is not considered at this time. Action: Possible voltage reduction at the next heat balance review.
4. Metal level is tracking the new reduced metal level target very well and with no yellow flame visible (physical observation). Action: Given the low voltage noise trend as well, a further small (0.5 cm) reduction in metal level along with an anode current distribution check is implemented at the Heat Balance Review. This should pave the way for reduced voltage target on this pot in the future.

Metal level reduction, in particular, must be undertaken slowly due to its profound effect on the ledge formation at the cathode surface, normally 0.5 to 1.0 cm in a month is a realistic goal, although it is seldom possible every month.

Rob looked at the potline voltage chart, one of the control points for the potline superintendent. No question, it was working; voltage was coming down (Figure 11.2).

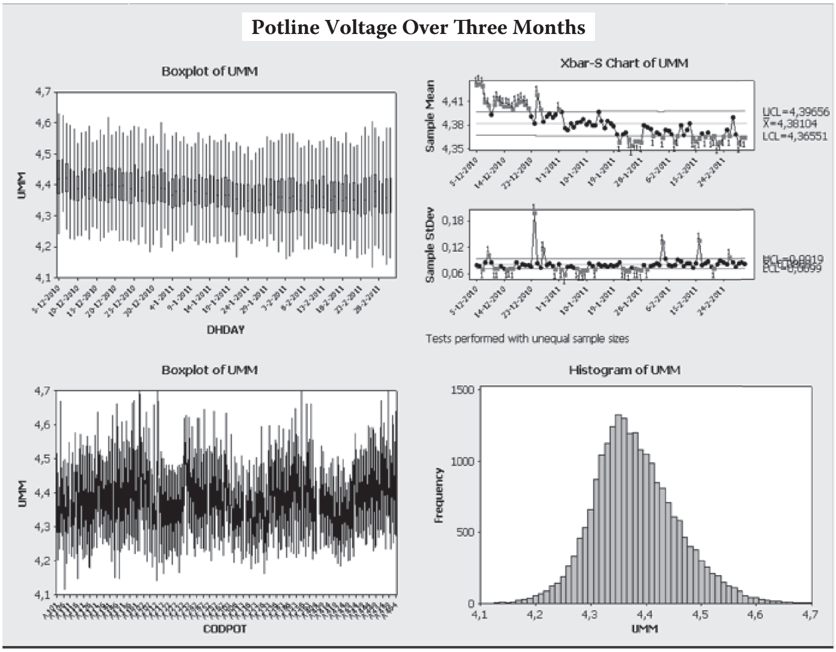

FIGURE 11.2
Potline voltage control chart over the last three months, showing actual daily average pot voltage (UMM) for the line. One of Rob's control points (process owner: potline superintendent).

But, there was something not right. Rob scanned the other control points. They showed

- increased long anode effects on some pots due to these getting sludged up badly, as they had experienced before;
- mechanical problems with anode jacking systems due to failure of jacks when making down orders during metal tapping; heavy bottom deposits and ledging on these pots; and
- looking closer at the voltage chart, the box and whisker chart showed a tendency for increased variation in voltage across the potline over the last month or so, even as the average voltage was still coming down.

Rob had that familiar, queasy feeling in the pit of his stomach. Something's not right—the needle in the haystack feeling. But, then the reality dawned. He had the tools now. He checked off

1. Most control charts in the healthy zone on a potline basis: temperature, CR, noise, cathode CVD and others.
2. Action was being taken on 95% of pots that were identified as needing action, within a week of the Heat Balance Review.

So, what was the problem? Monitor? Identify abnormality? *Response*?

Rob looked through the heat balance review logs on the system for the last two reviews.

- Soda additions were a feature. Going up. All the soda going in a small number of pots. That meant really cold pots, which in turn meant too much AlF3 added beforehand.
- Anode adjustments were going up as well, and repeated on the same pots, so not fixing the problems. That was because they were about material on the cathode, not the position of the anodes. Again, a small number of pots, but repeated adjustments. The response was to make the noise "go away" for a while.
- Extra voltage put on due to long AE (anode effect) times on individual pots, which had had too much alumina. Harder to trace, but there it was. These pots had been given special feed rates some time earlier, rather than finding the cause of the feeding or breaking problem.
- More compressed air use on sidewalls. A bad sign imprinted on Rob's brain, because it meant red shells and high superheat, due to out-of-control heat generation. The number of air hoses was still low but increasing.

These decisions being made at the Heat Balance Reviews were written down, authorized, and, therefore, auditable. And, here they were. Some of the same responses that had always been made for pots that *had a small problem*, problems that were then *dealt with*. Say no more.

In earlier days, the decisions would have been made as a matter of course without formal task assignment and would not have been auditable or even visible to management back then. Rob shook his head. The next challenge in *getting control* was revealed. The control responses themselves were actually part of the problem, not the solution. Each response he saw in the Heat Balance Review was about making the problem go away, fast, so they could move on to the next pot, rather than finding the reason and removing it *for all the pots in the future.* A new set of decision options was needed to go with the analysis phase of the periodic review process, decisions that were actually improving the state of the process by reducing causes of variation day by day.

"Steve, could you come in here, please. We have something to discuss." By now Steve knew the tone of Rob's voice and what it meant.

"Here we go. I can feel a new assignment coming on," Steve thought as he walked into Rob's office for the next installment of Rob's plan.

Control Responses That Improve the Process and Those That Do Not

The following examples in Table 11.1 are common control situations in aluminum processing. In these examples the control decisions which improve the process are shown, counterpointed by those which degrade it. In many smelters it is the latter, compensatory and easier decisions which tend to be used. However the former decisions, which implemented, produce a dramatically superior process over time

MYOPIC DISCOUNTING AND DELAYED REWARD

When people are faced with the following alternative courses of action, they will often choose the former:

- actions that will result in a short-term and immediately observable gain, with associated potential future detrimental effect; or
- a longer-term plan that will result in a safe and favorable long-term outcome with little or no immediately visible gain.

The psychological literature has many studies on cognitive biases, and these appear to be in action in such situations. Weber et al.[1] showed that "people are impatient and discount future rewards more when they are asked to delay consumption than when they are offered the chance to accelerate consumption." Kahnemann[2] drew the conclusion that "the neglect of duration combined with peak-end rule causes a bias that favors a short period of intense joy over a long period of moderate happiness."

Kirby and Herrnstein[3] used "hyperbolic discounting models of impulsiveness" in their experiments with subjects who were offered choices

TABLE 11.1

Control Decisions that Improve and that Degrade a Process

Process	Control Loop	Decisions That Improve Process	Decisions That Degrade Process
Carbon Anode Production: HTF System	Pitch temperature control (HTF not transferring enough heat)	Scheduling cleaning of the HTF system to reduce the heat transfer resistance, if the overall heat transfer resistance is already high, and testing of the HTF flashpoint to check the aging of the oil	Increasing HTF flow rate or temperature automatically to increase the driving force for heat transfer (leads to increased fire and explosion risks)
Carbon Anode Production: Green Carbon Plant	Green anode density control	Rejecting low density anodes and identifying and removing abnormalities in granulometry and in paste mixing to provide a better paste for compaction	Reacting to low green density at the vibroformer by increasing pitch content to increase density before baking; result is loss of control of baking through excessive volatile release
Aluminium Smelting: Control of the Operating Pots	Bath composition	Ensuring that the AlF3 addition rate remains near the rate of consumption over the medium term for each pot	Reacting aggressively to changes in temperatures, before understanding if they related to AlF3 mass imbalance, or heat imbalance (which is more likely)
Aluminium Smelting: Control of number of pots in circuit	Pot failure and rebuild control	Before pots start to fail, implement a pots at risk of failure monitoring system to identify the number of and reasons for these at-risk pots (which can be removed through better pot operations; respond with planned rebuild of pots and with planned pot cutout to minimize the number of pots at risk, as well as the number of pots out of circuit	If pots are failing unpredictably, hold other pots in circuit even though damaged, so that the number out of circuit is minimized and the failure age increases

TABLE 11.1 (*Continued*)

Control Decisions that Improve and that Degrade a Process

Process	Control Loop	Decisions That Improve Process	Decisions That Degrade Process
High Pressure Die Casting of Aluminum: Control of Melt Quality.	Melting furnace corundum control	Regular monitoring and cleaning of the furnace, including refractory replacement and (tower) corundum removal so that the melt inclusions are kept to a minimum and the temperature of the furnace is maintained as low as possible (reduced H_2%)	Running the furnace (e.g., a tower melting furnace) at high temperatures and without regular cleaning of the hearth or scrap addition points to achieve high productivity, but with increasing inclusion concentration

between delayed rewards. They found that the preferences of subjects typically reversed with changes in the delay time applied to rewards. An overwhelming proportion of their subjects "reversed preference from a larger, later reward to a smaller, earlier reward as the delays to both rewards decreased."

This is myopic discounting behavior, and it has been proved to be a powerful psychological precursor. It explains the bulk of the decisions that degrade the process, in Table 11.1. Such behaviors will not change unless the *instant gratification* decision alternative becomes unavailable to the person making the decision.

Kassam et al.[4] has recently put forward a concept termed *future anhedonia*, which is "the belief that hedonic states will be less intense in the future than in the present." This core belief is possibly linked to the myopic discounting precursor.

DECISIONS THAT IMPROVE CONTROL OF PROCESSES

From the examples in Table 11.1 and many others, a hypothesis about decisions that inherently improve control can be made. This hypothesis is based on work done by the authors in the field of bulk materials processing, and much broader, comprehensive studies of manufacturing in the work of W. Edwards Deming. It is summarized in the bullet points below, in the form of decision types that lead to better control.[5]

To get control, the following decision philosophy is proposed, consistently every day:

- To drive out variation through causally based control and improvement of all processes (a long-term control rationale applied to each control decision).

- To monitor and control the process, rather than the product, based on the customer value connections from factory floor to market.
- To reject measurements that have not been shown to be repeatable and reproducible.
- To identify and respond to data signals that indicate a dominant, unexplained cause of variation, although no out-of-specification product is being produced yet.
- To investigate and remove or correct the cause of these signals, rather than manipulating or compensating with another variable in an attempt to bring the process back to target.
- To monitor all aspects of the process state including the operational state of the equipment, and to respond to real changes in the state, based on the principles above; treat the machinery itself in the same way, and with the same care as the processing of the materials.
- To decide what human discretion is required before defining automatic control functions and operational interactions, based on the parts of the process where the variability is currently not understood (and where human reasoning, therefore, can add value).
- For critical variables, to determine the proportion of the variation that is driven by the existing automatic control strategy and the operational decisions, versus the proportion due to the design of the material transformation and unperturbed process design itself.
- To build a database and learn from control actions and process responses, both successful and unsuccessful.

Rob took the call in his office, although it had bounced back to Lee. It was the general manager, once again ringing the phone off the wall. There was no preamble.

"Rob we have a problem with costs. We need to do a reforecast for this year, now. And we need a new financial plan for next year. You'll need to spend three to four days with our accounting team to see where costs can be reduced, and then I want to know how. Obviously, it's going to involve people reductions."

"Okay, John. Give me a half hour here. I have to get things set up for the next week." Rob managed to sound casual, but his mind was racing.

The potroom was only just starting to become stable, and even that was a work in progress. People were getting used to new roles, new responsibilities. Several people in leadership roles had left because they couldn't make the change. Safety had improved, and it seemed to have taken place at almost the same pace, or maybe it was even earlier that this change had started. Rob remembered back to the aftermath of the digger incident and the resulting investigation. The journey hadn't been pain free. And now there was more to come. He knew that the cost of electricity was rising and that the price of metal had been sinking below US$2,000 again as the automotive and construction industries struggled globally.

Work Environment, Productivity, and Safety

Work environment, productivity, and safety are intrinsically and intimately connected. A report from the European Agency for Safety and Health at Work[6] concludes that "health and safety measures have an influence not only on safety and health performance but also on company performance." Furthermore, they also found that "… improved safety and health performance has positive effects on the company performance."

The following is a quote from "ROI of Safety,"[7] attributed to the president and CEO of the National Safety Council: "Organisations are beginning to realize that safety pays tremendous dividends in terms of lower workers' compensation and insurance costs, as well as improved employee productivity, morale and retention."

Krause[8] pointed out that "… employees who know they are cared about are receptive to engagement," and operational excellence parameters including production and safety are highly correlated. Arndt[9] wrote about Paul O'Neill, CEO of Alcoa from 1987 to 2000, who used "time lost to employee injuries" as the single major criterion for changing the company culture; he claimed that O'Neill believed "that to be a world-class company, it first had to become the safest." Quoting from Krause:[8] "In 1987, Alcoa's lost-time incident frequency rate was 1.86. In 2002, it was 0.12. In 1987, net income was $264 million on sales of $4.6 billion, with 35,700 employees and a market cap of $2.9 billion. In 2000, when O'Neill retired, profits stood at $1.5 billion on sales of $22.9 billion, with 140,000 employees. Market cap was $29.9 billion."

Along a similar vein, Sir John Harvery-Jones, Chairman of ICI from 1982 to 1987, in the Foreword to Kletz,[10] wrote: "My proudest boast during my stint as chairman was that for the first time ever ICI worldwide managed two consecutive years without a single fatal accident. This for me foreshadowed the fact that in the same two years we made record profits."

In the United States in 2003, business spent $170 billion a year on costs associated with occupational injuries and illness, and it was estimated that sound safety and health management systems can reduce injury and illness costs by 20 to 40%, which might determine whether the company is operating profitably or not.[11]

A survey by the Liberty Mutual Group, U.S.'s leading provider of workers' compensation insurance, reported that "financial executives who were surveyed said that the top benefits of an effective workplace safety program were predominantely financial in nature, e.g., increased productivity,[and] reduced costs." Furthermore, it was shown that 61% of the executives say that $3 or more were saved for each $1 invested in workplace safety.[12,13]

Krause[14] found that when safety starts to improve, employees become excited, engaged, and motivated, and "this positive change spills over and affects the entire organization—from productivity and quality to morale and culture."

Some researchers have analyzed the economic value of safety.[15] Veltri et al.[16] realized that many of the conclusions on the relationship between occupational safety and operating performance are based on anecdotal evidence and opinion surveys. They attempted to collect data on quality, productivity, and economic performance from 19 manufacturing firms, as well as data on safety perceptions of the firms' employees and managers. Their results showed that "as safety deteriorates, product quality and plant performance, based on internal and external measures, suffer. There are more scrap, more rework, and employees are less involved. Such outcomes are in line with the core concepts of total quality management, which would suggest that employees who do not feel safe in their jobs are not likely to do their jobs well." They concluded, "The results support the anecdotal evidence presented previously that good safety is good business. Safety and operating performance measures should be viewed as in concert with each rather than as competing entities."

Results are publicly available on the Internet on a major manufacturing company in New Zealand, New Zealand Aluminium Smelters, which won several high-level awards: NZ Business Excellence Awards 2007, and Riotinto Safety Awards, 2002.[17] We analyzed their performance in terms of the reported lost time injury frequency rate and productivity. The two sets of data are plotted in Figure 11.3.

In the period 1996 through 2000, it is clear that the dramatic trends in improved safety and improved productivity are matched almost as mirror images. What is even a more striking feature is the straight line relationship observed if the accident rate is plotted against the productivity on a semilogarithmic basis as shown in Figure 11.4.

The above two figures deserve some comments. Around the late 1980s, the company realized that the only way to influence behavior of staff 24/7 is through systems, systems that impact directly on the work people are doing when they are actually doing it. As can be clearly observed, the safety record improved very significantly with a gradual improvement in productivity in 1985 to 1996. In the period 1998 to 1999, STOP, a Safety Observation and Interaction system with staff, was introduced in conjunction with DuPont. This involves a one-to-one conversation about the work itself and what could go right/wrong during it, and how the employee and also the person doing the observation/interaction can take action to prevent these unsafe acts/conditions. This system, over

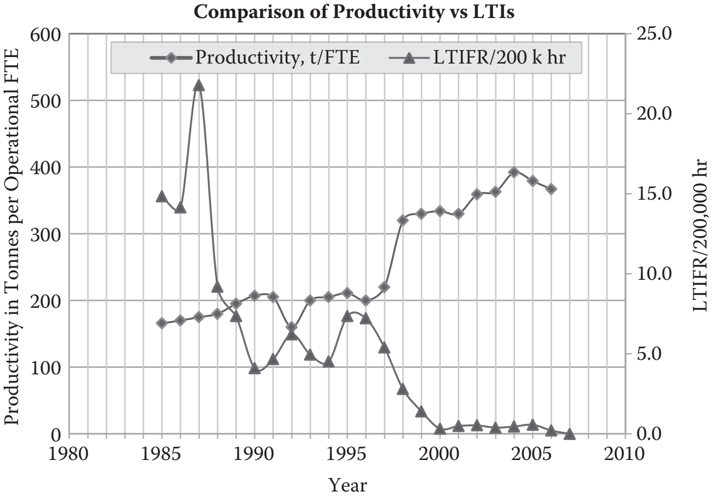

FIGURE 11.3
Comparison of productivity versus LTIs.

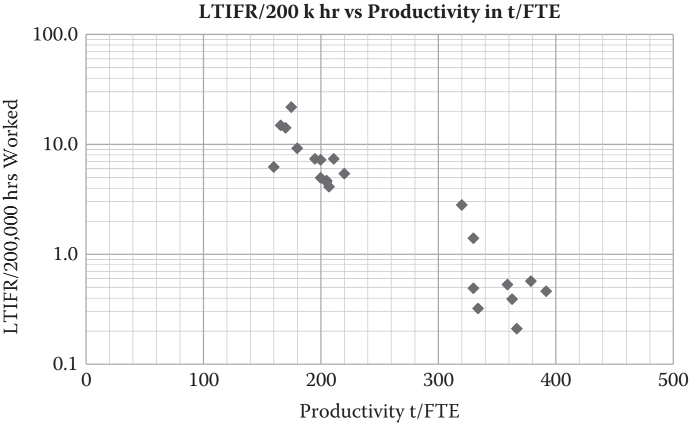

FIGURE 11.4
LTIFR/200 k hours versus productivity in t/FTE.

time, made a difference in the way employees controlled their own work behavior. At about the same time, the Riotinto Safety Audits also were implemented across plants, including NZAS. This system acted on the management layer, with no manager being able to avoid, hide, or forget about the safety actions for which he or she is held accountable. This system effectively controlled and eliminated existing safety conditions, and particularly those involving fatality risks. Taken together, these and other controls gave rise to a quantum leap in terms of improvement in safety and at the same time was at least partially responsible for productivity improvements as shown. Of course, technological changes, which required new process controls, were also implemented in this period, and the performance of these new systems was enhanced through the higher standard of work behavior that had been established by the staff.

Thus, in addition to showing genuine care for the workers, provision of a safe environment through safety control systems can form a platform on which enhancement of the whole enterprise is possible.

It should be added that consequent to this performance, the company was awarded the prestigious 2007 New Zealand Business Gold Award.

When taken in the context of not only the productivity increase but the reduction in energy consumption per metric tons of aluminum and the increase in the proportion of very pure metal produced, the above changes gave rise to a large improvement in the profitability of the enterprise.

For the first time in many months, Rob left the plant on time, but with a new question on his mind-how could the improvement in the smelter production process be used to transform the cost performance?

Exercises

1. In Figure 11.1, a number of process variables and outcomes are presented to assess the Periodic Heat Balance on a particular cell. What are the four interrelated balances being reported through the variables in this figure? How might a mass conservation imbalance affect the heat or electrical balances?
2. Referring to Table 11.1, select another industrial process you have worked in. Name two control actions that improve the process over time and two that degrade the process through retaining and increasing the causes of variation (discuss within groups).
3. What is a key indicator of decision making influenced by myopic discounting?

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12

Accelerating Removal of Variation

Rob drove along the straight and thought about the day. He had calculated what dropping one person per crew would do, plus cancelling his graduate engineers program as well as reducing two maintenance staff. The result was about a $350,000 reduction in cost per month out of his budget of $44 million per month. The problem was that wasn't anywhere near enough.

Out of the $44 million potroom costs, $27 million was electricity and $8 million was carbon. Another $3 million was maintenance materials—essentials for pot reconstruction and for the production machinery. There was the problem in a nutshell. There was only a $6 million discretionary spend per month (including salaries and contractors) out of a total of $44 million.

At least that was how the accountant saw it. However, there was another way of looking at the problem. If the usage of electricity could be reduced by 1 DC kWh/kg AL, that was $2 million per month. Reducing carbon consumption from 0.43 to 0.40 kg C/kg AL was worth another $0.6 million at $500 per metric tonne of coke. Reduced pot failures (through having no premature pot failures below 1,500 days) in combination with increased metal production through current efficiency and having all pots in circuit were worth another $0.5 million per month in cost per metric ton of aluminum based on the past five years of pot reconstruction and the number of pots that were continuously out of circuit in that time. The incremental benefit of that additional production of metal yielded another $1 million in net earnings or contribution, even at today's rather low metal price.

So, as he walked in the gate, the target was as clear to Rob as it could be. To save $3.1 million per month, out of $44 million costs, and earn another $1 million through incremental production would be a turnaround of $4.1 million in total contribution. And not by cuting people—by process breakthrough.

Rob came through the door in midstride. He had organized a meeting of the superintendents, both operations, process, and maintenance, to discuss the new targets for his production team. There was an air of anticipation in the room. This was born of confidence and achievement. A good place to be, thought Rob. The team was ready for the next step.

Ford and Steve had the production cost breakdown drawn up in grim detail on the whiteboard and were ready for the concrete steps aimed at reducing discretionary spending. Joe and the other maintenance superintendents had made a list of the maintenance expenditures that would be deferred or cancelled. The general manager's words had been heeded. Costs must be cut, now.

Rob wrote up his analysis on the whiteboard, without preamble: energy consumption, carbon consumption, pot failures, and metal production; no cost cutting on maintenance, gradual reduction in people, as allowed through improved process stability, and reduction in waste.

Confused looks around the table. Ford spoke for everyone.

"Rob, we have to reduce costs. I've been in the accountant's office all morning. We don't have time to spend on changing the process."

"We don't have time not to, Ford. $38 million out of $44 million per month goes on electricity, carbon, and pots. A fair proportion of this investment is wasted as heat or carbon dioxide or failed pots. That is where the real money is. There are other savings, of course, but that won't keep us out of the red. The process does have to change."

Steve spoke up. "Okay, we can see the benefit from what you are saying. It's big, alright. But, we just can't see how. It's taken us more than a year to get where we are today. Things are way better than before. But, you're talking about 10 times the improvement. Are you saying we haven't been trying?"

General nods around the room. It looked that way, all right. Rob realized that he had misjudged the situation. What he was saying seemed to be an implied insult. If the team could have reduced energy consumption from 14 to 13 DC kWh/kg AL, why hadn't they done it already?

Rob took a step back. "Okay, guys. You're right. We've done some things lately. Things to be proud of. Important things like getting control of our work and the potlines. But think about what we haven't got around to yet. Are there any problems that we haven't even scratched the surface of yet?"

"Airburn still kills us on some positions in the pot," Ford said as he started the ball rolling.

"We have at least 10 pots per week getting right out of control with alumina sludge and spikes across the potlines," added Steve. "Each one takes up to a month or more to fix after that. And a few get cut out of circuit eventually." He looked sideways at Ford.

Rob decided to let that one go for now.

"And 15 pots a shift getting anodes adjusted later on because of poor setting is probably the tip of the iceberg," Barry said having joined the meeting from line 1.

"Are we going to mention the green carbon plant breakdowns?" Joe reminded the team.

"Yeah, and the reject blocks you sneak through into the potroom, eh, Joe?" The grin on Ford's face said it all. They were friends. Old sparring partners.

Rob looked round the room. "So, we're not quite there yet, are we guys? Will getting some of these things fixed help us with these new process targets?"

Steve looked at Rob. He had something more to say.

"Okay, Rob. We all want to head that way. We can get there, but those problems have been around a long time—decades before I got here. I don't see how we can just wave the wand, and they'll go away." Steve's induction and "potty training" were still going on behind the scenes with the guys on crew.

"Come on, Steve. Rob's just given you your tasks, mate. Don't get depressed." Barry's slow smile. But, Steve wasn't finished.

"What I'm trying to say, Rob, is this isn't a plant improvement project here. It's a breakthrough you're asking for. No plant I know of has changed their energy consumption by that much in five years, let alone over one year. That's not what we're geared up for here. We need some real different skills. A different approach. Its won't be a part-time job either. How are we going to do it? We're supposed to be reducing people."

There was silence now. The magnitude of the job was sinking in.

Point well made. The targets were there, but the pathway was not, and Rob was out of bullets.

"Okay, guys. Let's do some more thinking about how we attack this. We have a few days before we have to present the plan to John and the accountants. Let's see what we can come up with. Steve, I want you and Ford and Joe to work with me on this tomorrow." Rob ended the meeting, Bloodied, but not beaten.

Rob took a long walk down potline 1 and across the east passage onto potline 2. Crew 4 was on day shift, and he saw Jimmy McLaren opening tap holes with a crowbar on the pots to be tapped that morning. He was sweating and bending his back. The bar was hitting, breaking through crust, plunging through into the molten bath, or sometimes bouncing off hard crust.

"Morning, Jimmy. Careful with that bar, mate. Why don't you use the new tap hole breaker?" Rob was referring to the improvement recently made to the breaking mechanism on the pots, which allowed semiautomated breaking of the tap hole rather than manual breaking. Operators on line 3 had come up with the idea.

Rob remembered that Jimmy had a pretty good temper on him, and his glance at Rob carried a storm warning.

"Well, if the bloody thing would unfold right, then I might be able to do that, Rob. So far, two out of the five tap hole breakers have seized up hinges. I reckon we don't have the knowledge on the right type of metal or bolts for that temperature. Why don't we ever ask the experts on this sort of thing?"

Jimmy was a foot away from Rob. The bar was in his hand. Red hot at one end.

"Okay, good point, Jimmy. What do you plan to do about it?" Rob asked.

"I've told you now, Rob, so you can fix it." Jimmy had his standard answer prepared.

Rob held out his hands. “Look at these, Jimmy. Two hands and one brain. Same as yours. How about you and your brain go and see the equipment improvement engineer and explain this idea of yours, and let him know you’re working with me on finding a solution. I’ll check up on him later to make sure he’s got your message.”

Rob moved off down the line, before Jimmy could find any other uses for the crow bar. As he walked, Jimmy’s words came back. *Why don’t we ever ask experts on this sort of thing?*

Well, why don’t we? Rob thought. But who were the experts on rapid smelter improvement, or even just on rapid improvement in general, or process breakthrough?

Back in the office, Rob dialed a number from memory. His old professor back at the university, who was an expert in the various new process analytics techniques for complex processing plants, including use of multivariate statistics and process monitoring. Maybe the time had come to broaden and deepen the expertise available; 1 DC kWh/kg wasn’t just going to fall in his lap.

Process Breakthrough and Smelting Pots

What is the next frontier for removing variation from a process that is more than 100 years old? In aluminum smelting, there is structural variation that has been a consequence of the unperturbed design of the process, persisting through many generations without being removed; problems such as airburn of anodes, alumina sludging on the cathodes. What is the point of attack for these persistent issues that are not yet solved? And, to what extent are they really the result of loss of control over the process? This question requires databased approaches that can take into account the multivariate nature of materials processing. However, this is never enough by itself to enable rapid improvement or breakthrough.

The insight to make the right hypothesis about what is happening in a complex process, especially one with poor observability like aluminum smelting, comes from an underpinning knowledge about the process mechanisms themselves, supported by the databased approach. In smelting cells, and in many other processes, these mechanisms have their roots in the conservation of mass and energy—and especially as if affects the most pervasive process in smelters: alumina feeding.

In the qualitative model of Figure 12.1, an alumina feeding dynamic is triggered by reductions in bath superheat, due to inhibition of alumina dispersion and dissolution caused by local freezing of the bath near feeder holes. Freezing occurs around the breaker itself and around the added alumina to prevent access by liquid bath to the alumina surface for dissolution.

This dynamic disturbs the fragile, control algorithm-relating voltage or resistance increase due to low average alumina concentration. Low alumina concentration increases the pot voltage, and this increase is

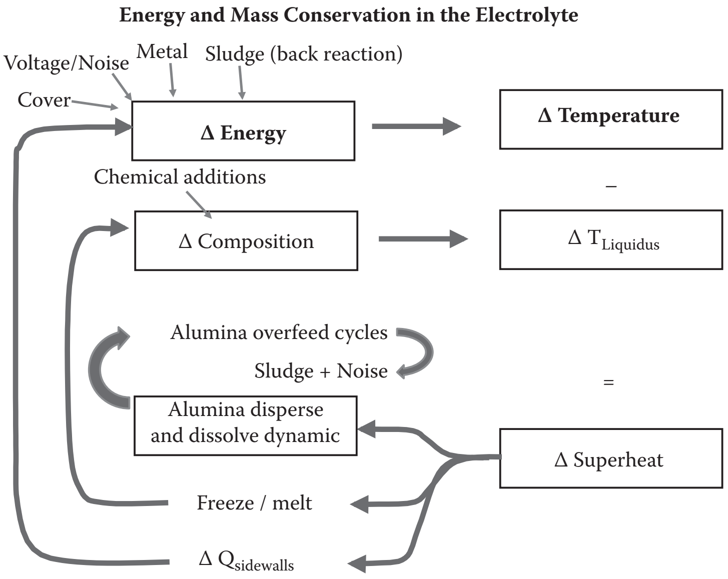


FIGURE 12.1
Energy and mass conservation in the electrolyte of a smelting pot. (Adapted from Taylor, M. P. 1997. Challenges in optimising and controlling the electrolyte in aluminium smelters. Paper presented at the conference on Molten Slags, Fluxes, and Salts, pp. 659–673.)

detected as "resistance rise" or "resistance slope" by the control algorithm, which then prescribes alumina overfeeding cycles. If low alumina concentration prevails in the electrolyte due to poor dissolution, the result is many more alumina overfeeding cycles over a period of hours, and these quickly exceed the capacity of the pot to dissolve or electrolyze the raw material. Sludge is the only possible result, and metric tons of sludge can build up in only one eight-hour shift when this dynamic is triggered. Anode short circuiting and spiking, along with very high temperatures and back feeding of alumina, are the delayed, severe consequences of this process. It may take a month for this to run its course on a high amperage (300–600 kA) pot technology. More detail on alumina feeding developments through advanced process monitoring are explained below.

Monitoring and Control Strategy

The established relationship between voltage (measured variables) and alumina concentration (unmeasured variables) via theoretical voltage/alumina concentration curves[1] as shown in Figure 12.2, has led to control system improvements for aluminum smelting cells from 1975 to 1990. A key recent breakthrough for system improvement is the recognition of variability patterns and signals deviating from these established theoretical curves and their integration into an automated control system.[2]

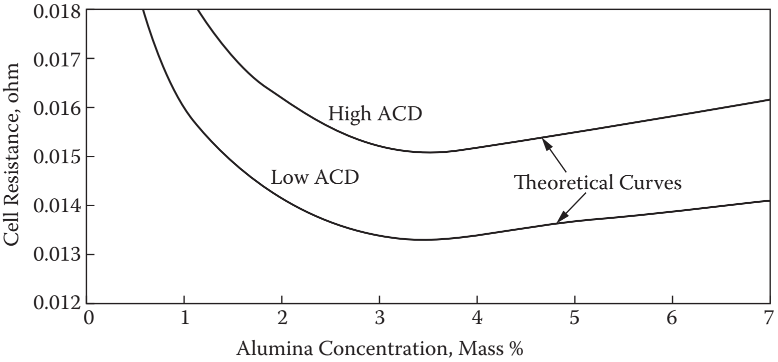


FIGURE 12.2
Theoretical cell resistance versus alumina concentration at a constant anode cathode distance (ACD). (Redrawn from Kvande, H. 1993. Process control of aluminium reduction cells. In *Introduction to aluminium electrolysis: Understanding the Hall-Heroult process*, eds. K. Grjotheim and H. Kvande. Dusseldorf: Aluminium-Verlag.

Variability patterns within an alumina feeding cycle can be used for detection and diagnosis of faults in the aluminum smelting process and prediction of future consequences.[3]

As seen in the industrial example, nine overfeed–underfeed cycles over a period of 11 hours were observed from a cell in an aluminum smelter, where each observation had an average duration of five minutes. The ninth cycle relates to an anode effect. A change in rate of increase in cell resistance was observed in the ninth cycle. This change has triggered earlier overfeeding (shorter underfeeding) than previously, and it is also possible to move to even shorter time intervals between individual feeds, in order to eliminate anode effects based on the rate of changes in resistance.[4] However, in many cases, including this one, a more subtle acceleration in the pattern of the cell voltage trace and the overfeed–underfeed cycles prior to this last cycle actually indicate problems that eventually cause an anode effect (or a flash anode effect), such as a blocked feeder, crust falling into the cell, or low alumina dissolution.[2] For example, increases in resistance during overfeeding may indicate feeding problems or a sudden increase in alumina concentration,[5] for example, due to collapsing of a pile of alumina into the bath from around the feeder hole. There is a clear need to develop a model capable of isolating the causes of anode effects based on the changes of the cell voltage and resistance patterns within the overfeed–underfeed cycles (Figure 12.3).

Changes in higher frequency (greater than 1 Hz) cell voltage patterns (not shown here) within an overfeed–underfeed cycle also may indicate the presence of anode spikes that cause short-circuiting between the anode and the metal. These anode spikes decrease the production

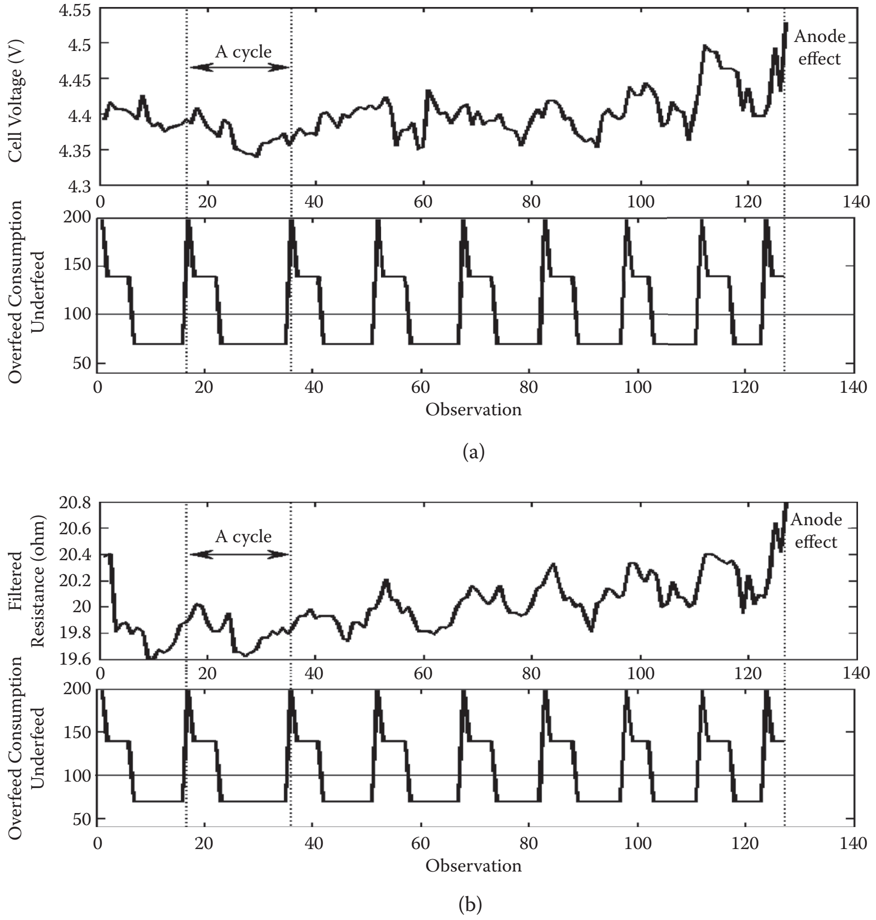


FIGURE 12.3
(A) An industrial example of cell voltage and (B) cell resistance and feed rate for point feeding that ends with an anode effect.

rate and cause subsequent overheating of the cell resulting in instability in the process. In the aluminum smelter example shown below, anode spikes are detected using: (1) soft sensing based on an increase of cell temperature by more than 15°C and a decrease in alumina feeding by more than 10% and (2) measuring process variables, such as current distribution and temperature at each anode every 24 hours. Based on these methods that really document the consequences of spikes, the occurrences of anode spikes are recorded.

Figure 12.4 shows a series of feed cycles from a cell in a smelter where the last cycle ended with a recorded anode spike. Using the methods described above, it is difficult to ascertain when the anode spike started

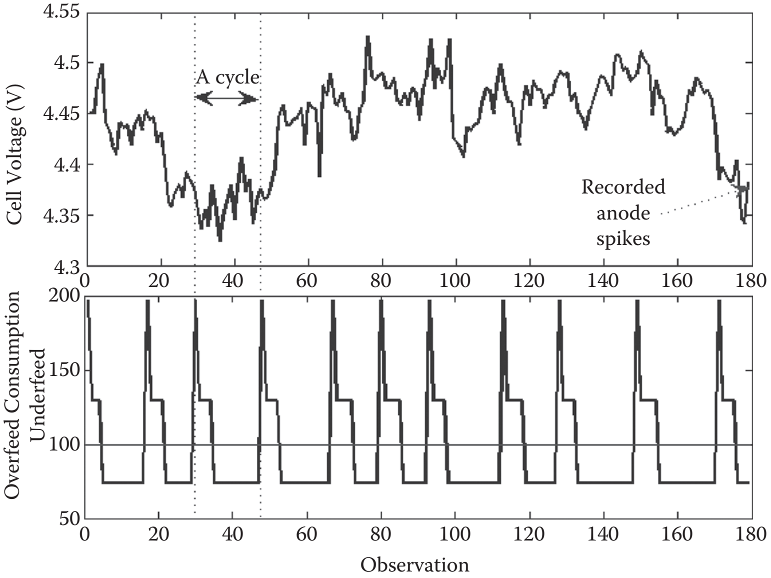


FIGURE 12.4
An industrial example of cell voltage and feed rate for point feeding that ends with recorded anode spikes.

to occur because anode spikes are only able to be detected after they have been occurring for a period of time. Therefore, there is also a need to investigate the potential of using a statistical approach for the early detection of anode spikes by observing the changes of the variability patterns within the overfeed–underfeed cycle, and, in particular, by observing the connection between alumina feeding abnormalities (giving rise to sludge formation) and the subsequent spiking of particular anodes under the accumulated sludge material.

The above statistical approach should be developed to track the progression of the causes of feeding abnormalities and spiking, rather than just the consequences.

Hotelling Statistics for Multivariate Control

THE HOTELLING T^2 STATISTIC

In multivariate processes, it is usually the case that a number of variables are not independent, so that univariate control charts do not adequately describe the variation. A multivariate statistic that takes into account any correlation structure that exists is the Hotelling T^2.[6-9] Chen and Taylor[10] describe this problem in detail for the case of the smelting pot bath in which the temperature and composition are intimately related through the mass and energy balance described in Figure 12.1. For the two variables involving temperature, X_T, and excess AlF_3, X_A, this is given as:

$$T^2 = \frac{\sigma^2_{X_A}\sigma^2_{X_T}}{\sigma^2_{X_A}\sigma^2_{X_T} - \sigma^2_{X_A X_T}}\left[\frac{\left(X_A-\bar{X}_A\right)^2}{\sigma^2_{X_A}} + \frac{\left(X_T-\bar{X}_T\right)^2}{\sigma^2_{X_T}} - \frac{2\sigma X_A X_T\left(X_A-\bar{X}_A\right)\left(X_T-\bar{X}_T\right)}{\sigma^2_{X_A}\sigma^2_{X_T}}\right]$$

The Hotelling T^2 also can be calculated for more than two variables, in which case it involves the use of vectors and matrix algebra.

The upper control limit (UCL) is calculated as follows and uses the F statistic:

$$T^2 = \frac{p(N-1)}{(N-2)}F_\alpha$$

In the above equation, p is the number of variables that is equal to 2 in the case under consideration. N is the number of data points, and F_α is the F statistic for a significance level of α, with degrees of freedom for the numerator = p, and degrees of freedom for the denominator = (N – 2). In Figure 12.5, the UCLs for the 95% and 68.2% confidence levels are calculated to be 6.335 and 2.365, respectively.

The UCLs are also plotted in Figure 12.6, which is a direct plot of temperature versus excess aluminum fluoride. In this plot, the UCLs translate into ellipses, and they are known as *control ellipses* or *confidence ellipses*. The specification range for the temperature (950–970°C) and excess aluminum fluoride(10–14%), the mean temperature ±2σ, and the

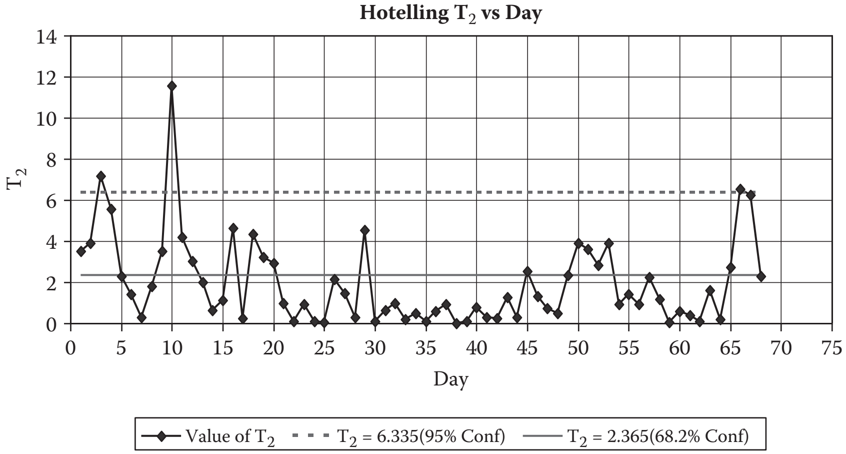


FIGURE 12.5
Hotelling T^2 with the control limits for 95% and 68.2% confidence.

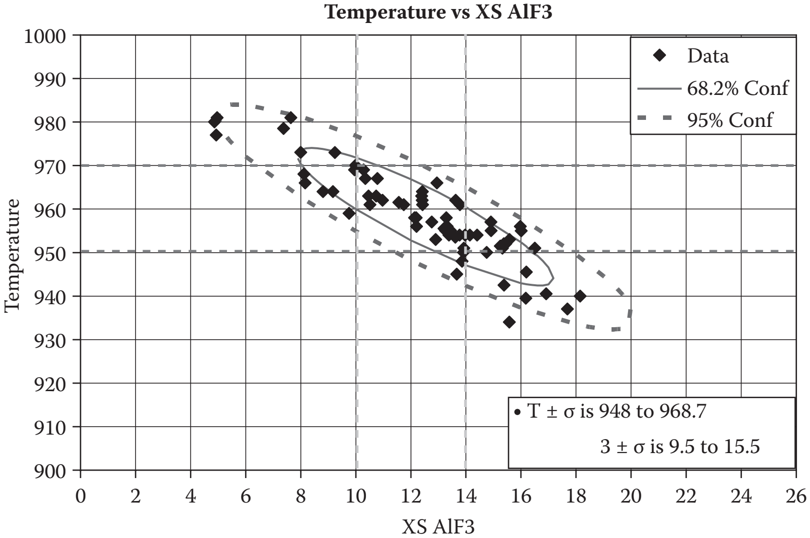


FIGURE 12.6 (See color insert.)
Plot of temperature versus XS AlF_3 with the control or confidence ellipses.

mean excess aluminum fluoride ±2σ also are shown. The mean temperature ±σ are 948 and 968.7°C, respectively, and the mean excess aluminum fluoride ±σ are 9.5 and 15.5%, respectively.

Inspection of the control ellipse in Figure 12.6 against the actual data points plotted clearly show that the Hotelling T^2 statistic is the appropriate method to use for this system, which exhibits a strong correlation.

DISCUSSION OF THE HOTELLING T^2 CONTROL ELLIPSE

To facilitate discussions, Figure 12.7 shows the data points, the control ellipse representing 68.2% confidence, the specification range (rectangle formed by solid lines), the mean ± one sigma region (rectangle formed by broken lines), and various areas marked A, B, C, and D. Data points that fall within regions C and D are normally considered to be under statistical control in the univariate situation as they are within the mean ±σ range of the variables under consideration. However, as given by the Hotelling T^2 analysis, they, in fact, are not in statistical control. Thus, regions C and D would have been undercontrolled if they were erroneously treated as for the univariate situation.

On the other hand, regions A and B are outside of the mean ±σ region but are considered to be in statistical control according to the Hotelling T^2 analysis. Thus, if treated as if univariate conditions apply, these regions would have been overcontrolled.

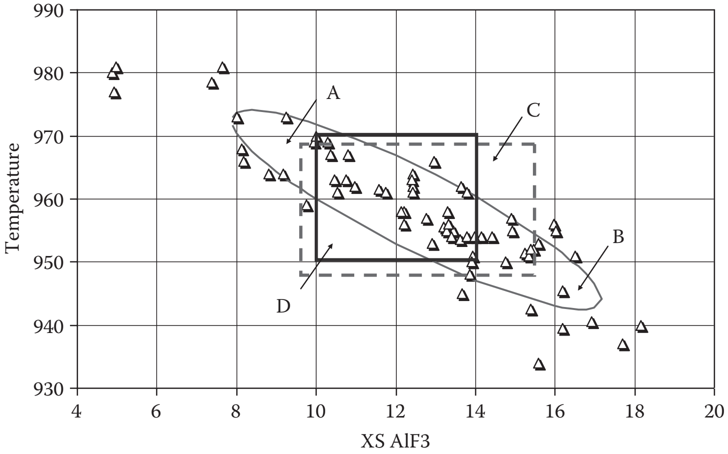


FIGURE 12.7
Regions of "overcontrol" and "undercontrol" in the graph of temperature versus XS AlF_3.

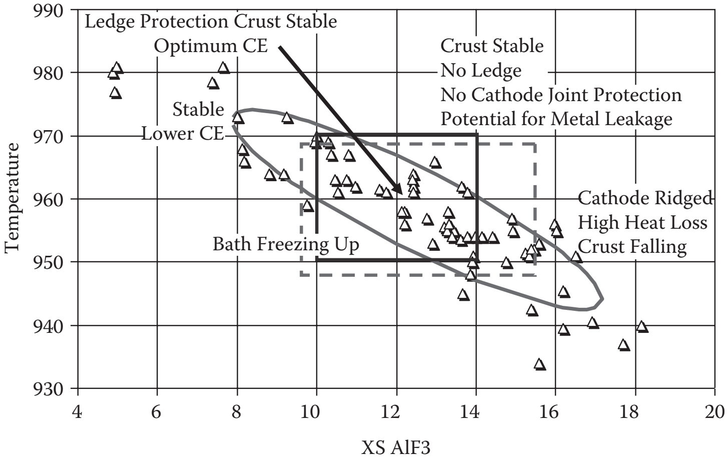


FIGURE 12.8
Plot of temperature versus XS AlF_3 with the Hotelling T^2 control ellipse, the specification range, the mean ±σ region, and various operating conditions.

IMPLICATIONS FOR SMELTER CONTROL

Operational experience at the great majority of smelters over the past 20 years has determined that the optimum efficiency and cell life are obtained if the cells can be maintained within the box marked by solid lines, as shown in Figure 12.7. In fact, there are sound physicochemical and thermochemical reasons for this related to the process design as indicated earlier.[10] Figure 12.8 shows some of the consequences of being outside the box, overlaid on the control ellipse. It, therefore, is of considerable concern that the natural variation observed on many cells takes the temperature and composition well outside of the box marked by solid lines as indicated by the ellipse. The potential seriousness of these process deviations, if they should continue over a period of time, and a dominant "return to target immediately" control culture can cause the following to occur:

1. Tampering decisions at the extremes of the ellipse (Zones A and B) where the process is behaving normally, resulting in heavy-handed actions, which increase the variation in temperature or composition, further broadening the control ellipse.
2. No decision and no investigation of cause when the cell is inside the specification zone, but outside the ellipse, despite the fact that an assignable cause probably exists if in Zone C or D in Figure 12.7.

The control ellipse provides a basis for rational decision making, which will prevent both of these problems. Simply, a point outside the ellipse needs to be investigated because it is an opportunity to remove a cause of variation. Points inside the ellipse should not be responded to, although patterns of variation may still provide evidence of process structure and ideas for a corresponding control system response if the cause can be diagnosed. The control objective is to reduce the ellipse dimensions over time and move the majority of observations into the central area of the ellipse, which coincides with the specification zone.

Symbols

D: Standardized Euclidean distance (SED)
F_α: The F statistic for a significance level of α
N: Number of data points
T^2: Hotelling T^2 statistic
X: A variable
$\bar{X}$: Mean value of variable X
Z: Standard deviation unit

Greek

Σ: Standard deviation
σ^2: Variance
χ^2: Chi-squared distribution

Subscripts

i: the i^{th} variable
T: Temperature
A: Excess aluminum fluoride(AlF_3)
p: Number of variables

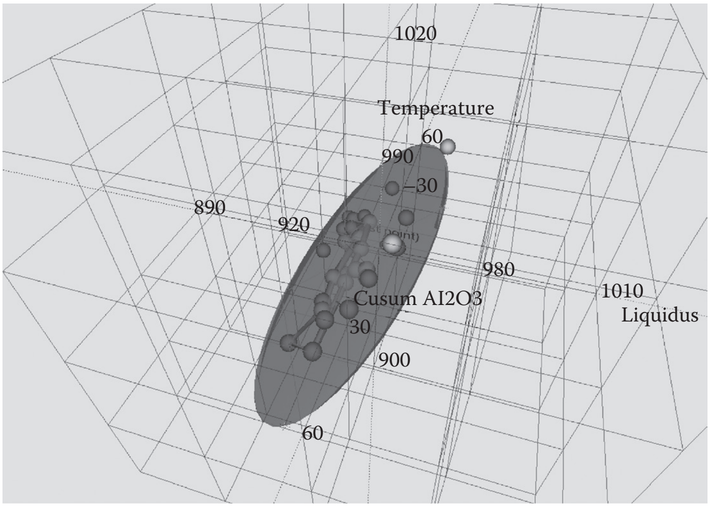


FIGURE 12.9 (See color insert.)
3D pot operating envelope by Hotelling statistic at 95% confidence, using bath temperature, liquidus temperature, and alumina feed rate (represented by its CuSum).

The alumina feeding dynamic depicted qualitatively in the process mechanism of Figure 12.1 can be incorporated in the Hotelling control envelope if the CuSum of the feed rate to the pot is plotted along with the bath temperature and the composition. In the plot in Figure 12.9, Marco Stam et al.[12] plotted the liquidus temperature directly because this was measured in preference to the AlF3% concentration. The resulting envelope and latest data point is available immediately after the bath temperature/liquidus point measurement is made (cryotherm probe by Hereaus Electro-Nite Ltd, Hanau, Germany).

In Figure 12.9, the red data points are outside the envelope and, therefore represent special causes in the control of the process that will then be diagnosed and traced back to specific events or pots issues by the control system, for investigation by operators or engineers.

Unfortunately aluminum smelting (along with other complex and distributed processes) has a high degree of natural variation due to its structure—more than 500 separate electrolytic reactors in a single facility, high variability, and batch addition of carbon and alumina raw materials, an electrolytic bath that is superheated only 5 to 10°C above its primary freezing point. This low superheat is combined with the presence of solid electrolyte phases (side ledge, top crust, and cathode sludge) that are prone to melting and solidification, respectively, giving rise to severe thermal or electrical current flow disruptions.

The result of this high variability is that the Hotelling multivariate envelopes in Figure 12.8 and Figure 12.9 are larger than the feasible operating range (e.g., the specification limits shown in Figure 12.8). Therefore, by the time special causes can be identified statistically through breaching the envelope, or even forming patterns within the envelope, there may be serious process consequences, such as freezing, sludge, spikes, anode effects, overheating, and loss of efficiency. Feeding issues also are identified later by Tessier et al.[12] in their multivariate statistical process monitoring studies using the Hotelling statistic as being an important source of special causes and disruption to pots.

The challenge in process breakthrough is to use the "grey box" modeling of Figure 12.1, together with a more intensive, multivariate monitoring technique and examination of all key variables in the pot process to produce insights about the alumina feeding dynamic for example, *before* it has serious consequences for the pot. If this can be achieved, then the "safety constraints" imposed by operating plant management on pot ACD (anode current distribution) and voltage can be relieved so that higher energy efficiency is immediately delivered and without the destructive consequences of pots going out of control.

Rob stood at his whiteboard, pen in hand. He wrote:

$$4.4\text{ V} \times 298/93\% = 14.1\text{ DC kWh/kg AL}$$

Current efficiency was improving slowly as more pots stayed inside the T/AlF3/ACD operating envelop. Process management was finally "breaking out."

And 94% current efficiency was at least achievable in the future, especially with healthy pots, without cathode or anode problems.

So:

$$13.1\text{ DC kWh/kg} = ?\text{ V} \times 298/94\%$$

The required voltage for 13.1 DC was 4.13 V, 270 mV lower than the present average. Still a sobering calculation.

However, Rob actually had seen pots in the plant operate at this voltage or near it for periods of minutes or even an hour. More than one. As Ford had told him, the trick was to keep them there. After some time, the temperature dropped, feed control was lost, and the pot developed noise. Symptoms were yellow flame at the corners or red anode stubs. But, generally, there was a cooling effect first, rather than an immediate heating effect as a result of extra heat generation.

Thus, there was a heat balance problem with this voltage, requiring a reduction in pot heat loss. But, there was apparently not a physical anode cathode distance limitation—at least at 7 to 8 mm below the present ACD. Metal production was not damaged immediately by these lower ACDs.

It was clear to Rob that the new process design would need to have a lower level of liquid metal, a much better anode cover, and lower heat extraction from the top, and maybe a way of insulating the sidewalls. Rob thought he would have to leave that last one for another day, because there was another issue, a bigger one. There was no way of telling in real time whether any of the pots were starting to move outside of this new, narrower, and more demanding operating envelope.

At lower ACD, the team had noticed that small problems like a mis-set anode or a feeder malfunction became big problems really fast—within one to two hours. Then, loss of current distribution, noise, and increased voltage followed. Even worse than that were the pots that did not respond quickly with voltage problems. These pots could just fill with sludge due to overfeeding, and this was more prevalent with cold pots as well. Then massive overheating and anode failure could occur and not be fully recovered for weeks or a month as Steve had said in the meeting. That happened multiple times every week, even at the present pot voltages.

This was at the root of Rob's call to his old "control" professor. They needed a different level of process monitoring. A predictive technology. Something that could be acted upon to prevent a pot from leaving the envelope *before it did so*.

Principal Component Analysis (PCA): Application to Overfeeding Cycles and Sludge, Plus Spikes as a Result

PRINCIPAL COMPONENT ANALYSIS (PCA)

Principal component analysis, or PCA, is a useful statistical technique that was developed over the course of the twentieth century.[13] There have been thousands of applications of PCA over the years in many areas, such as psychology, education, quality control, chemistry, market research, economics, anatomy, and biology.[14] PCA is a data reduction method that is able to project most of the important information from a large multivariable process onto a reduced dimensional PCA model. A PCA model is usually built from a few principal components. These components are the result of decomposing a data matrix of process variables **X** using PCA. Statistically, PCA will decompose such a data matrix **X** ($K \times J$) comprising a number of highly correlated variables (R), into:

$$X = TP' + E = \sum_{r=1}^{R} t_r p_r^{'} + E$$

where X is a two-dimensional data matrix of J process variables sampled over K time intervals. This data matrix, X ($K \times J$) represents the large multivariable process, whereas t_r is the R principal components that form the PCA model, and E is assumed to be random errors.[15] The principal components (PCs) are defined by the R loading vectors (p_r) that are the eigenvectors of $\boldsymbol{X}$ ($K \times J$), and these vectors are used to transform the data, $\boldsymbol{X}$ ($K \times J$), into its R principal components. The number of principal components for the PCA model is lower than the number of process variables, i.e., R is less than J. The R loading vectors provide a direction of maximum variability in the process so that one can observe the process using the model built from a few principal components, as most of the variability in the data can be expressed in these few principal components.

Geometrically, the PC variables are the axes of a new coordinate system obtained by rotating the axes of the original system (the xs). The new axes represent the directions of maximum variability.[16] These new axes are defined by the PC loading vectors, which transform the original variables to PC variables and, therefore, play an important role in the transformation. In Figure 12.10, for example, the first loading vector, P_1, is in the direction of the greatest variance where most of the data are

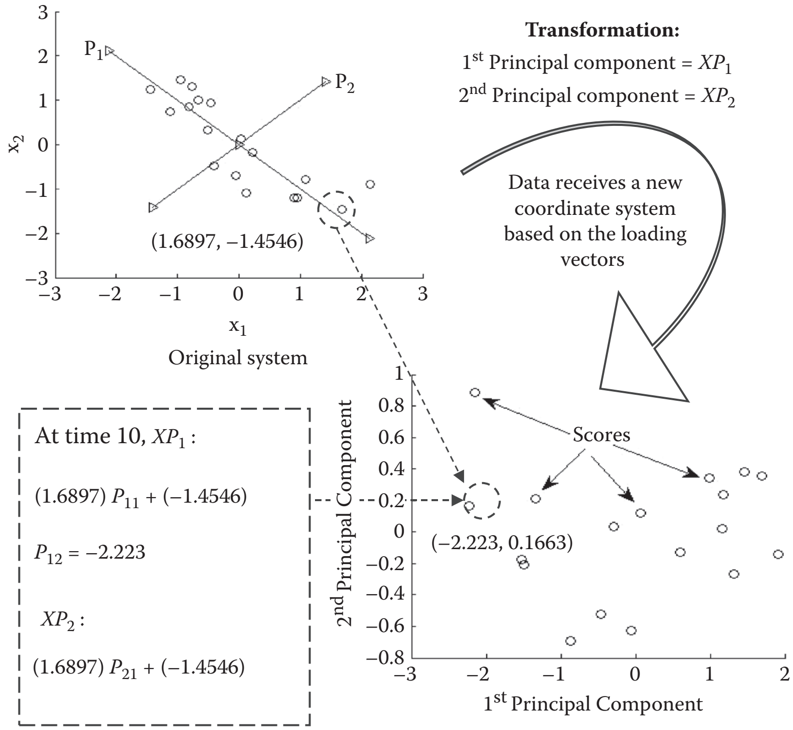


FIGURE 12.10
A transformation from original variables to principal component (PC) variables.

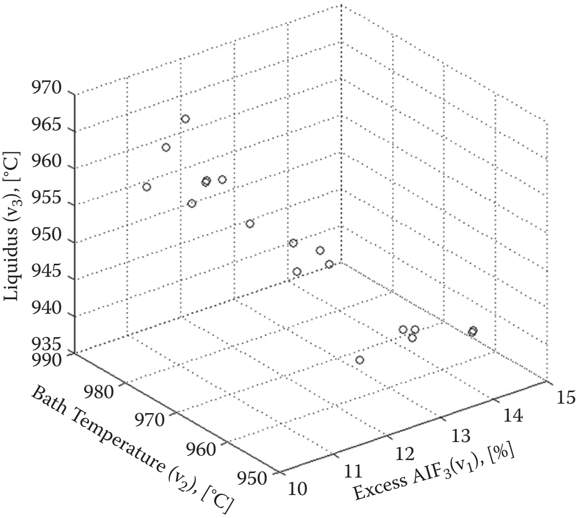


FIGURE 12.11
Scatter plot of three process variables showing a strong correlation.

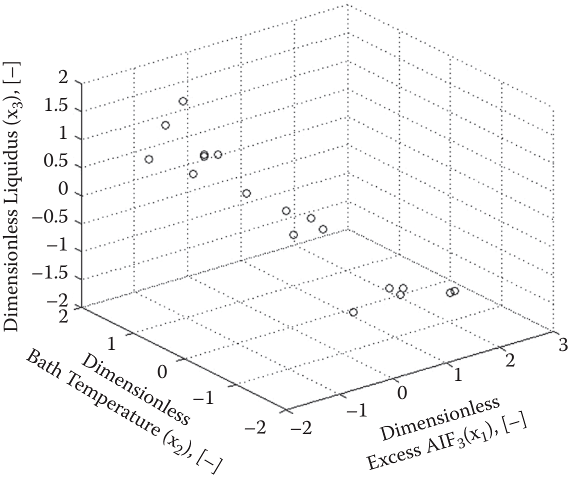


FIGURE 12.12
Scatter plot of the standardized data.

clustered along P_1. However, fewer data are clustered along the second loading vector, P_2, which is orthogonal or perpendicular to the P_1.

Loading vectors P_1 and P_2 are used to transform the original data from two process variables to the first and the second PCs, respectively. As a result, scores that are the individual data points in the PC variables can be visualized in a scatter plot defined by the first and the second PCs. This scatter plot, which also is known as a projection space, a score plot, or a reduced space, becomes the new coordinate system after the transformation.

APPLICATION OF PCA TO REAL DATA FROM AN ALUMINUM SMELTER

The computations in PCA are relatively straightforward[14] and involve six basic steps for obtaining correlated variables, standardizing data, calculating the covariance matrix, calculating the PC loading vectors, choosing the PC loading vectors, and deriving the scores for PC variables. A brief explanation for each step is given below using data from a real aluminum smelter.[3]

Obtaining Correlated Variables

Data that exhibit a moderate or high correlation are needed for PCA, because poorly correlated data will give PC variables that are similar to the original variables.[4] Therefore, one of the advantages of using PCA (to reduce high-dimensional data to low-dimensional data) is unlikely to be achieved. This advantage of PCA is explained below in Choosing the PC Loading Vector and Forming a Feature Vector. Three process variables from aluminum processing v_1, v_2, and v_3 (Table 12.1) are used as an illustration of PCA in this section. The process variables, excess AlF_3 (v_1),

TABLE 12.1

Excess AlF_3 (v_1), Bath Temperature (v_2), and Liquidus, (v_3) Process Data

Observation (daily)	v_1 [%]	v_2 [°C]	v_3 [°C]
1	14.47	959.00	939.27
2	13.28	960.00	942.23
3	12.08	969.00	953.19
4	11.52	977.00	959.98
5	10.96	982.00	963.76
6	10.39	980.00	960.54
7	11.28	977.50	960.27
8	12.17	957.00	942.01
9	13.06	956.00	943.24
10	13.96	953.50	942.97
11	13.12	956.00	944.17
12	12.29	966.00	952.87
13	11.46	971.00	956.58
14	11.11	976.00	961.01
15	10.77	975.00	959.44
16	11.17	980.50	967.72
17	11.58	963.00	953.00
18	11.98	961.00	953.78

temperature (v_2), and liquidus (v_3), are highly correlated so that they are suitable for using with PCA. The strong relationship between process variables is shown in the clustering of most of the data along a line in the scatter plot.

Standardizing Data

As the variables obtained in the above step may have several different units and the variance between those variables might be substantial, the variables are standardized by subtracting each variable from its mean and dividing by its standard deviation.

The standardized variables x_1, x_2, and x_3 in Table 12.2 represent the variables v_1, v_2, and v_3 in Table 12.1 after the standardization. The scatter plot of this standardized data () has axes that differ from the scales of the scatter plot of the original data (), but both scatter plots indicate a similar pattern. All the variables are dimensionless and have zero mean and unity variance.

Calculating the Covariance Matrix

The covariance matrix (***C***) is used to measure the relationship between variables. The following equation shows the formulation for the calculation of ***C***, which is cov(X,Y).

TABLE 12.2

Standardized Data (x_1, x_2, and x_3)

Observation (daily)	x_1, [–]	x_2, [–]	x_3, [–]
1	2.1434	−0.8931	−1.5779
2	1.0910	−0.7911	−1.2401
3	0.0386	0.1276	0.0093
4	−0.4568	0.9442	0.7821
5	−0.9523	1.4546	1.2131
6	−1.4477	1.2504	0.8464
7	−0.6633	0.9952	0.8160
8	0.1210	−1.0973	−1.2658
9	0.9053	−1.1994	−1.1253
10	1.6897	−1.4546	−1.1557
11	0.9564	−1.1994	−1.0188
12	0.2231	−0.1786	−0.0272
13	−0.5102	0.3317	0.3946
14	−0.8132	0.8421	0.8999
15	−1.1162	0.7400	0.7214
16	−0.7596	1.3014	1.6649
17	−0.4030	−0.4849	−0.0128
18	−0.0463	−0.6890	0.0760

$$\mathrm{cov}(X,Y) = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{(n-1)}$$

The resulting covariance matrix from Table 12.2 gives absolute values of the correlation coefficients between x_1, x_2, and x_3 above 0.8, indicating a strong correlation between them.

Calculating the PC Loading Vectors

Finding the loading vectors that define the PC variables is fairly easy.[17] The PC loading vectors are the eigenvectors (***P***) for the covariance matrix. Each *P* captures a different amount of variance represented by the eigenvalues (***L***). The relationship between the matrix ***C***, matrix ***P***, and matrix ***L*** can be defined as:

$$CP = LP$$

The eigenvectors, p_1, p_2, and p_3 in this example are plotted over the scatter plot, as shown in Figure 12.13. It can be seen that the third eigenvector, p_3, shows the most intense cluster of data. The loading vector p_3 has the largest eigenvalue because it captures most of the variability of the data.

Choosing the PC Loading Vector and Forming a Feature Vector

In PCA, the first PC loading vector must be based on the greatest variance. Therefore, the eigenvectors are reordered by eigenvalues, in order

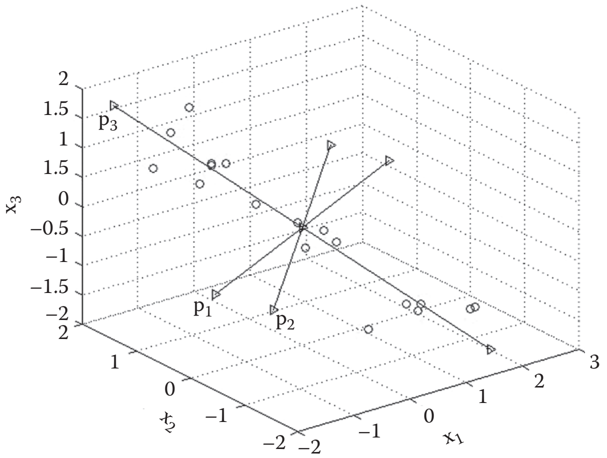


FIGURE 12.13
Scatter plot with eigenvectors.

of highest to lowest so that the PC loading vectors are in order of significance.[18] For the example, as p_3 captures the most variability of the data, p_3 is arranged to be the first eigenvector, and its eigenvalue is arranged accordingly.

The number of PC loading vectors that should be retained to form the feature vector is dependent on the variance captured by the PC loading vectors. The percentage of the variance captured by every PC (EV) is simply calculated by using the following equation:

$$EV_i = \frac{l_i}{\sum_{i=1}^{m} l_i} \times 100$$

where l is the variance or eigenvalue, i is the selected PC loading vector, and m is the number of PC loading vectors. The bar chart for the percentage of variances for the PC loading vector for the three process variables used in this example is shown in Figure 12.4.

Overlaying is a line plot of the variances. This line plot is a scree plot that indicates the positions of the eigenvalues from large to small. The number of PC loading vectors forming a feature vector is based on the position of an elbow, which is a sharp change in the slope that occurs in the line segments joining the points of the variances. The first PC loading vector, for example, accounts for 92.74% of the variance, and there is a clear elbow between the first and the second PC loading vector. In this case, the first PC loading vector is sufficient to explain the variance, but, if the first two PC loading vectors are selected, they will give a more accurate analysis because they account for 98.17% of the variance. Therefore,

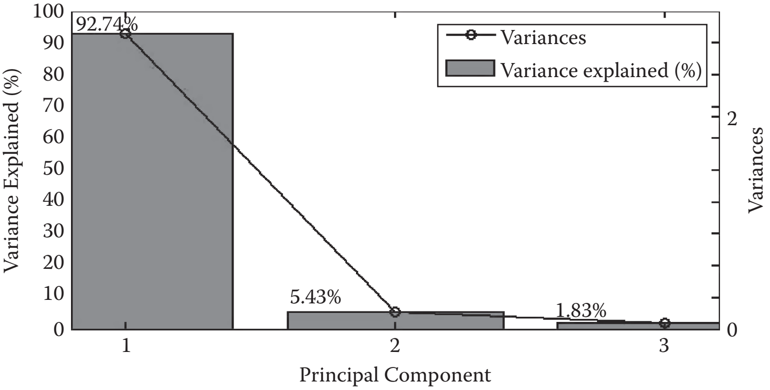


FIGURE 12.14
The first two principal component (PC) loading vectors account for 98.17% of the total variability.

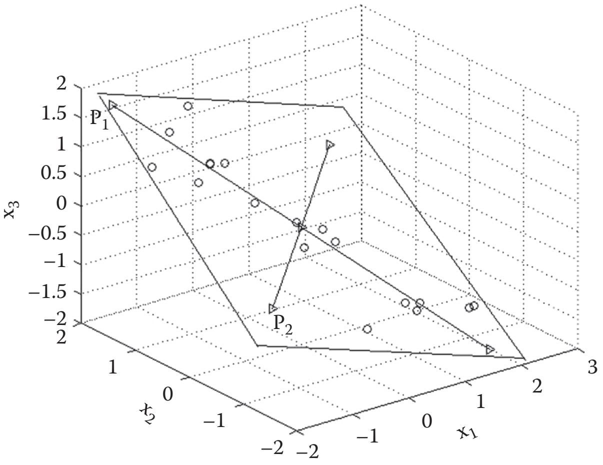


FIGURE 12.15
Scatter plot with the first two loading vectors retained.

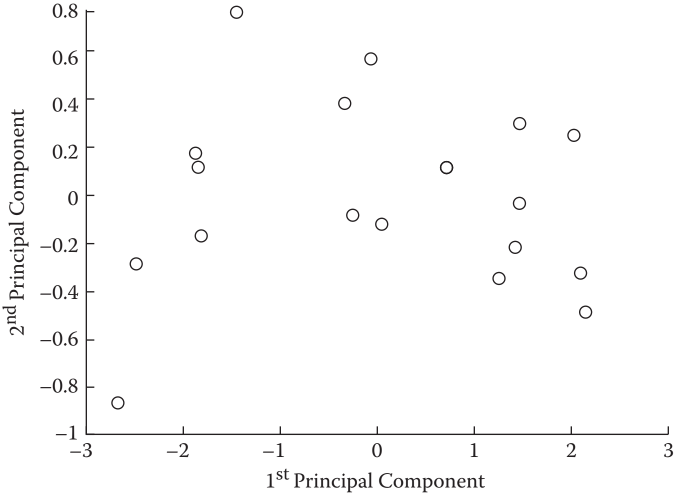


FIGURE 12.16
Scatter plot for the first two principal component (PC) variables used to form a new coordinate system.

the first two PC loading vectors from matrix ***P*** are retained to form a "feature vector."

The feature vector captures most of the variability on a plane (flat surface), as shown in Figure 12.15. This plane represents the main patterns or features of the data. In PCA, we are interested in analyzing components that can best describe the pattern of the data. Therefore, the feature vector that now constitutes the principal components of the data is used to transform the original variables into PC variables.

Another way to determine the number of PCs is based on the "broken stick" rule, which may be expressed as the point in the curve between the variance and the number of PCs that also can be expressed mathematically.[15,19]

Deriving the Scores for the PC Variables

Based on the selected PC loading vectors or the feature vector, the original variables are transformed into PC variables. Each data point of the original variables receives a new coordinate to form a score. For this transformation, the matrix ***P*** that contained the retained loading vectors is transposed so that each row in matrix ***P*** represents each loading vector.

The scores (t_{ij}) then are derived by using the following equation:

$$t_{i1} = p_{11}x_{i1} + p_{12}x_{i2} + \ldots + p_{1p}x_{ip} \ (p_{\mathrm{ij}} \text{ is the element in } p_1)$$

$$t_{i2} = p_{21}x_{i1} + p_{22}x_{i2} + \ldots + p_{2p}x_{ip} \ (p_{\mathrm{ij}} \text{ is the element in } p_2)$$

…

$$t_{ir} = p_{r1}x_{i1} + p_{r2}x_{i2} + \ldots + p_{rp}x_{ip} \ (p_{\mathrm{ij}} \text{ is the element in } p_r)$$

where r is the number of retained PC loading vectors, p_{ij} is the element for each loading vector, p is the number of process variables, and i is the number of data points.[17] Each score defined by the same loading vector forms a PC variable.

The overall scores for the first PC variable (t_1) and the second PC variable (t_2) are shown in Table 12.3. These PC variables form the axes of the new coordinate system () and represent the most important information contained in the data.

APPLICATION TO OVERFEEDING CYCLES AND SLUDGE, PLUS SPIKES AS A RESULT

We have seen that PCA is a useful technique to analyze the principal variations in multidimensional data. In this section, we will see how knowledge of process variation (elucidated by statistical process monitoring, e.g., with PCA) combined with traditional engineering process control and qualitative knowledge of the process (overfeed and underfeed cycles, and material and energy balance relationships) can be used for fault detection and diagnosis, and prediction of future consequences during operations. This overarching strategy is illustrated in Figure 12.17.

A "cascade" fault detection system based on PCA was designed and implemented to detect multiple faults: an anode effect, an anode spike, and other faults (a blocked feeder and low alumina dissolution).[3] This system

TABLE 12.3

Scores for the First and Second PC Variables

Observation	t_1	t_2
1	−2.6576	−0.8666
2	−1.8037	−0.1576
3	0.0573	−0.1048
4	1.2638	−0.3363
5	2.0926	−0.3217
6	2.0402	0.267
7	1.4302	−0.2077
8	−1.4459	0.794
9	−1.867	0.1963
10	−2.477	−0.2785
11	−1.8334	0.1327
12	−0.2457	−0.0712
13	0.7126	0.1349
14	1.476	−0.0198
15	1.484	0.3176
16	2.1601	−0.4857
17	−0.0593	0.5976
18	−0.3273	0.4095

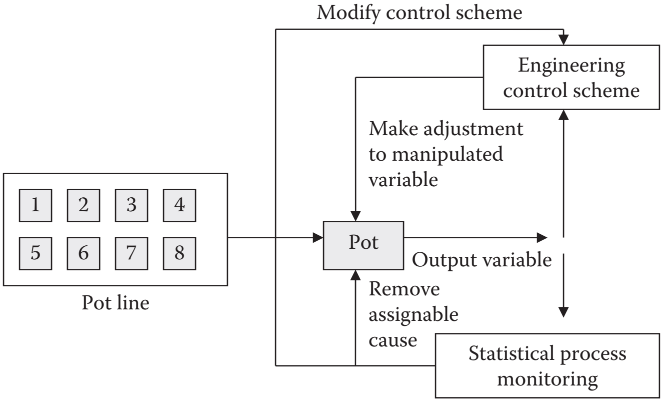


FIGURE 12.17
An overview of process control strategy of aluminum reduction pots incorporating both Engineering Process Control (EPC) and Statistical Process Control (SPC).

was termed a “cascade” system because of the incorporation of the cascade of overfeed and underfeed cycles into the control system. In order to detect multiple faults, the system was divided into two parts. The first part identifies when a fault has occurred (fault detection), and the second part determines which fault has occurred (fault diagnosis). The second part would only be executed when a fault has been detected either by a T^2 chart or a SPC chart. In order to demonstrate how two abnormalities—anode spikes and anode effects—can be detected by using the cascade fault detection system, two examples from an aluminum smelter are presented below.

Anode Spike Detection Example

An anode spike was recorded in pot 2003 in the smelter at 4.16 p.m. on May 23, 2009. One anode was affected, and the action taken by the operators was to change the anode. At the time when the anode spike was recorded by operators, it was not certain when this anode spike had begun to occur. Furthermore, at this time the cascade fault detection system was not implemented as an online module of the process control system of the smelter. Early detection is advantageous. Therefore, in this example, an investigation was carried out to ascertain exactly how early in the cascade fault detection system process an anode spike could be detected.

The data stored from the start of the anode change to the recording of the anode spike was retrieved in sequence from storage and sent to the "cascade" system so that the results from the data could be compared to the online result. In an online situation, the process data would be input in real time through the data acquisition system of the existing process control system. Figure 12.18 shows the logical flow from the aluminum reduction pots to the main operator's screen for the cascade fault detection system and for the first part of Module I of the cascade fault diagnosis system, which is a PCA-based fault diagnosis.

Monitoring the data set revealed evidence of faults in this example where some of the Hotelling's T^2 and SPE values were above the control limits (). Further analysis of these faults using PCA-based fault models

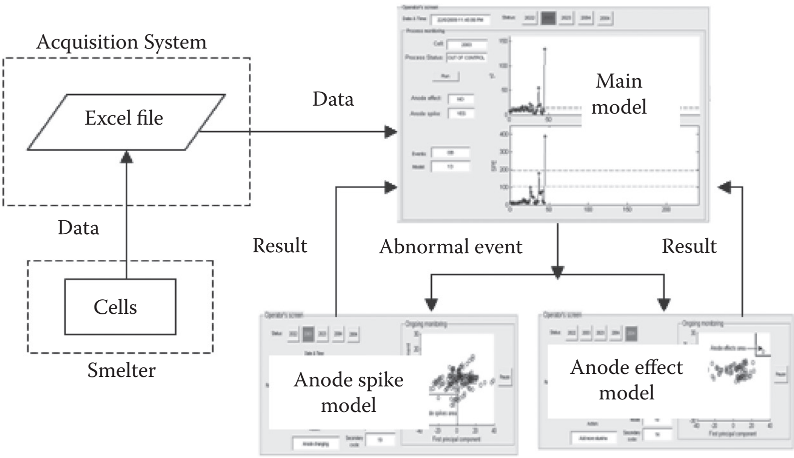
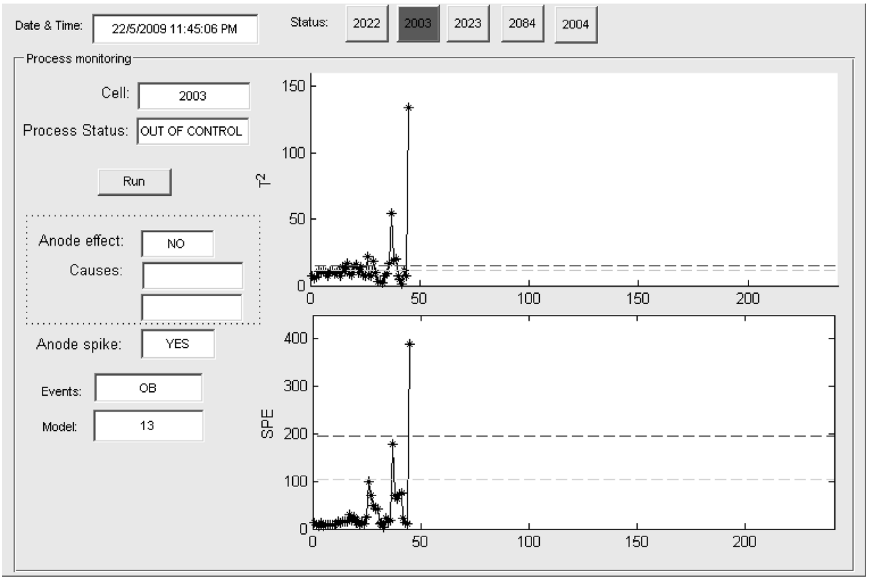


FIGURE 12.18
Logic flow from cells to the cascade fault detection and diagnosis system.



Date & Time: 22/5/2009 11:45:06 PM

Cell: 2003

Process Status: OUT OF CONTROL

Anode effect: NO

Causes:

Anode spike: YES

Events: OB

Model: 13

FIGURE 12.19
Example operator screen for the anode spike detection example showing a possible anode spike was detected at 11:45 p.m. on May 22, 2009.

(anode spike and anode effect fault models) showed that the related scores entered the "anode spike" area or "problem area" in the underlying PCA plot. The operator's screen indicated this situation by a change in the color of button for pot 2003 from green to red, the status of the process from IN CONTROL to OUT OF CONTROL, and the status of the anode spike detection from NO to YES (Figure 12.19).

In this investigation, the time when the scores of the above samples entered the "problem area" was compared with the time the anode spike was detected by the operators. There were three time periods prior to the recorded time of the anode spike, during which scores entered the "problem area," as indicated in Figure 12.20 for the cell voltage and Figure 12.21 for the screenshots of the anode spike model of the system.

The scores entered the "problem area" first at 11:45 p.m. on May 22, 2009, during the 13th secondary cycle after an anode change (Figure 12.21a). The scores entered the "problem area" second during the 16th secondary cycle at 4:45 a.m. on May 23, 2009 (Figure 12.21b). The scores again entered the "problem area" at 10:15 a.m. on May 23, 2009 (Figure 12.21c). This last (the 19th) secondary cycle shows the deviation of cell voltage error data samples from the reference trajectory (Figure 12.22). The reason why the scores travelled in and out of the "problem area" was due to the compensatory actions that had been taken by the operator to increase the low value of the total resistance of the cell while not realizing a spike

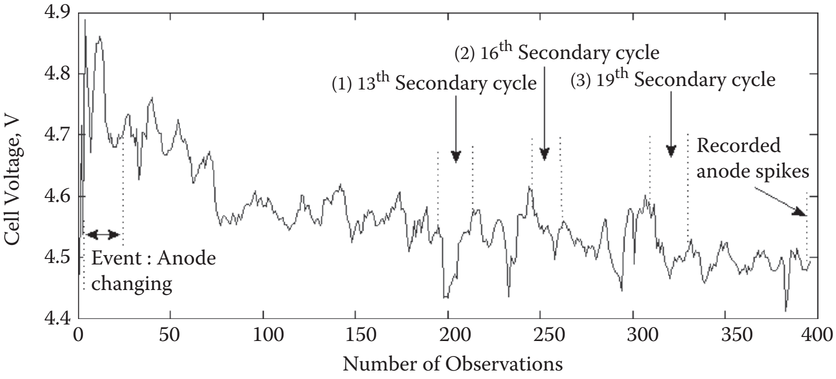


FIGURE 12.20
Cell voltage data from the anode spike detection example, indicating the secondary cycles involved in the detection of the anode spike.

had developed. Because the anode spike protrusion still remained at the affected anode, the occurrence of the anode spike was once more detected, this time by the cascade fault detection system.

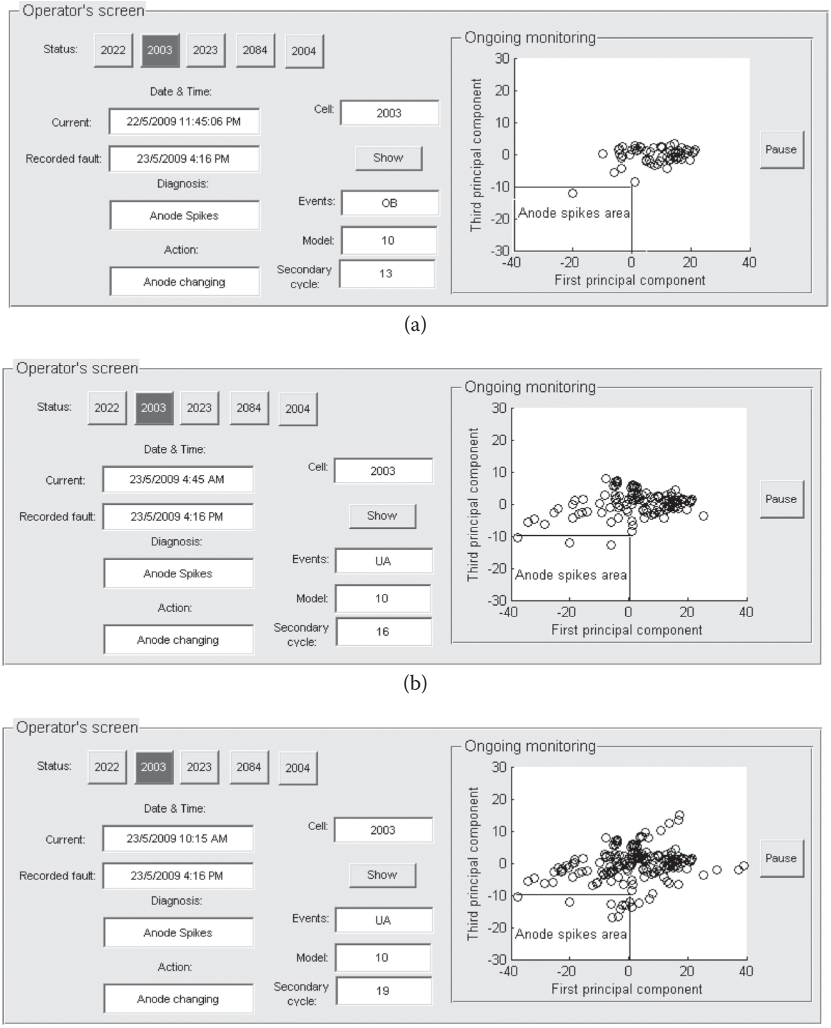
Overall, the cascade fault detection system, through its main and fault models, appeared to detect the anodes spike at an earlier time, for example, before the anode spike was recorded by the operator in the aluminum smelter. The system proved to be faster than the customary process used for the detection of anode spikes in three instances: (1) 16 hours and 31 minutes earlier, (2) 11 hours and 31 minutes earlier, and (3) 6 hours and 1 minute earlier. In this particular case, an anode was changed due to this detection. If an anode spike can be detected early in the process, as in this particular instance of usage of the cascade fault detection system, the operator can take corrective action earlier by going to the cell and either changing or cleaning the anode. This will stop the short-circuiting that can increase the pot temperature to a level that could cause cell damage.

ANODE EFFECT DETECTION EXAMPLE

In this example, an anode effect was recorded at 8:45 a.m. on April 21, 2009. An investigation was subsequently undertaken to discover exactly how early in the operating process the cascade fault detection system would be able detect an anode effect.

The samples were replayed from storage as for the example above. The occasion when the scores entered the “anode effect area” was on the same day on which the actual anode effect occurred, but approximately 20 minutes earlier, as can be seen in Figures 12.23 and 12.24.

In addition, during the period immediately prior to the anode effect, the alumina concentration in the pot was low so that it was feeding at a higher rate. Therefore, by predicting the occurrence of the anode effect a



(a)

Date & Time:
Current: 22/5/2009 11:45:06 PM
Recorded fault: 23/5/2009 4:16 PM
Diagnosis: Anode Spikes
Action: Anode changing
Cell: 2003
Events: OB
Model: 10
Secondary cycle: 13

(b)

Date & Time:
Current: 23/5/2009 4:45 AM
Recorded fault: 23/5/2009 4:16 PM
Diagnosis: Anode Spikes
Action: Anode changing
Cell: 2003
Events: UA
Model: 10
Secondary cycle: 16

(c)

Date & Time:
Current: 23/5/2009 10:15 AM
Recorded fault: 23/5/2009 4:16 PM
Diagnosis: Anode Spikes
Action: Anode changing
Cell: 2003
Events: UA
Model: 10
Secondary cycle: 19

FIGURE 12.21
Anode spike detection plots indicating the three different times when the scores entered the anode spikes area: (a) during the 13th cycle, (b) during the 16th cycle, and (c) during the 19th cycle.

few minutes earlier, the cell could be fed earlier to increase the alumina concentration, or other action could have been taken to improve the rate at which alumina was dissolved in the bath. This would prevent the anode effect from occurring and, most importantly, intervene before the pot was seriously overfed with alumina.

Before the system detected that the process was going to have an anode effect, there were many scores that violated the control limits of the

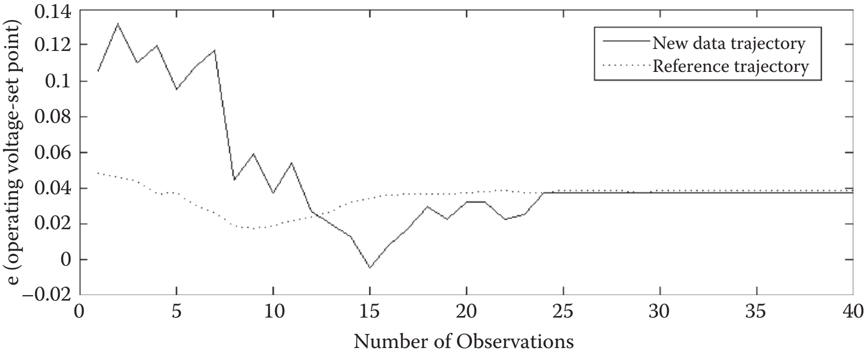
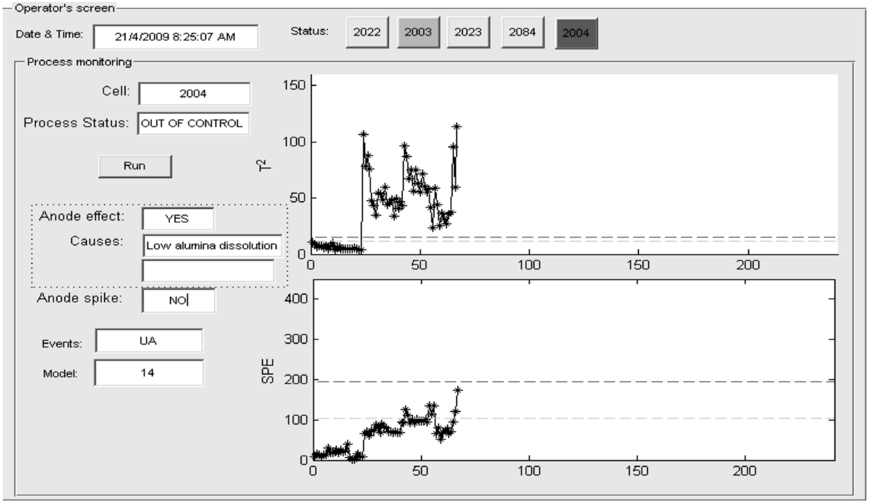


FIGURE 12.22
Deviations of cell voltage error data samples during the 19th secondary cycle from the reference trajectory.



Date & Time: 21/4/2009 8:25:07 AM

Cell: 2004

Process Status: OUT OF CONTROL

Anode effect: YES

Causes: Low alumina dissolution

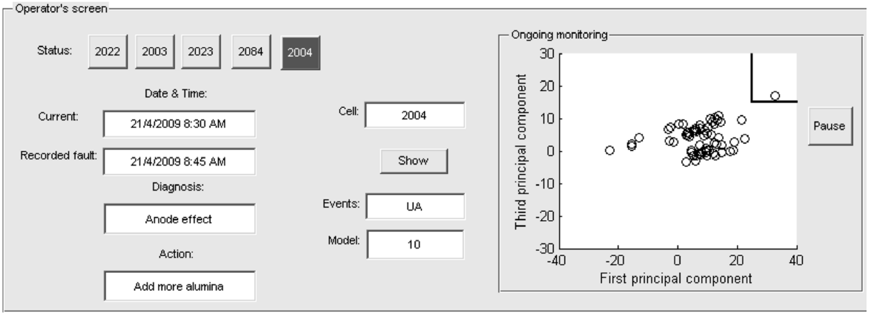
Anode spike: NO

Events: UA

Model: 14

FIGURE 12.23
Example operator screen for the anode effect detection example showing that a fault detected at 8:25 a.m. was an indication of an impending anode effect.

monitoring charts. This shows that this system can detect other faults that were most probably the root cause of the anode effect. By using the diagnosis module from the "cascade" fault detection and diagnosis system, the root cause of the anode effect was identified as low alumina dissolution. Based on this information, the operator could go to the pot to check whether the temperature was low or whether there was a feeder blockage or mechanical problems. If taken, this corrective action could prevent future reoccurrences of anode effects due to this particular root cause.



Operator's screen

Status: 2022 2003 2023 2084 2004

Date & Time:

Current: 21/4/2009 8:30 AM

Recorded fault: 21/4/2009 8:45 AM

Diagnosis: Anode effect

Action: Add more alumina

Cell: 2004

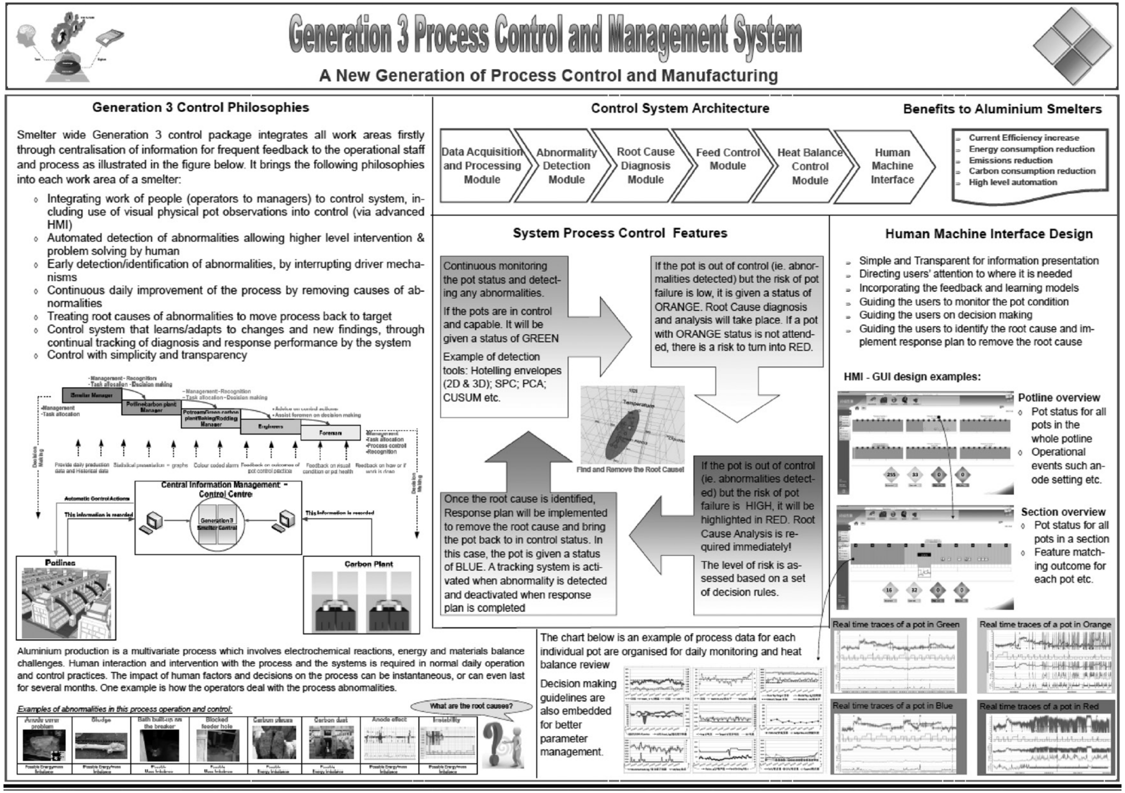
Events: UA

Model: 10

FIGURE 12.24
An example of anode effect detection where the time of detection was at 8:30 a.m., 15 minutes earlier by the fault model than by the smelter operation.

Generation 3: A Practical Example of a Control System which Uses Multivariate Process Monitoring and Advanced Diagnostics

A newly developed control package shown schematically in Figure 12.25 based on a patent by Taylor and Chen[2] takes into consideration the multivariate interactions of the operating parameters. A module in the software package encapsulates the philosophy to diagnose and remove root causes, thus ensuring control responses are corrective rather than compensatory, and that variation is reduced over time in the smelter. It provides a human guidance process that detects and identifies the type of abnormalities and restores the operation to a normal and stable state. In one module, the software guides the interpretation of data by choosing two or three lead indicator variables at a time and calculating the Hotelling T^2 statistic based on current and historical data extending back to a predetermined stable period. Various multidimensional "zones" are defined based on the variables chosen. The zone where the most recent data point is situated is considered, taking into account the path traced in terms of the direction and distance traversed in each step, i.e., the vectors that make up the path. Analysis of the paths taken and the zones traversed allows the determination of whether the process is stable, is moving out of the stable zone, or is "pin balling," changing state too rapidly. From a consideration of the zones and the paths traced by the vectors and any other historical markers captured by the control system, process risks, such as sludge formation or anode spiking, are highlighted, and the type and mechanism of the abnormality identified. This enables appropriate response plans to be formulated and executed in order to remove the root causes and restore the operational stability before the process has moved into an unpredictable or damaging state.



Generation 3 Process Control and Management System

A New Generation of Process Control and Manufacturing

Generation 3 Control Philosophies

Smelter wide Generation 3 control package integrates all work areas firstly through centralisation of information for frequent feedback to the operational staff and process as illustrated in the figure below. It brings the following philosophies into each work area of a smelter:

- Integrating work of people (operators to managers) to control system, including use of visual physical pot observations into control (via advanced HMI)
- Automated detection of abnormalities allowing higher level intervention & problem solving by human
- Early detection/identification of abnormalities, by interrupting driver mechanisms
- Continuous daily improvement of the process by removing causes of abnormalities
- Treating root causes of abnormalities to move process back to target
- Control system that learns/adapts to changes and new findings, through continual tracking of diagnosis and response performance by the system
- Control with simplicity and transparency

Aluminium production is a multivariate process which involves electrochemical reactions, energy and materials balance challenges. Human interaction and intervention with the process and the systems is required in normal daily operation and control practices. The impact of human factors and decisions on the process can be instantaneous, or can even last for several months. One example is how the operators deal with the process abnormalities.

Examples of abnormalities in this process operation and control:

Control System Architecture

Benefits to Aluminium Smelters

- Current Efficiency increase
- Energy consumption reduction
- Emissions reduction
- Carbon consumption reduction
- High level automation

System Process Control Features

Continuous monitoring the pot status and detecting any abnormalities.

If the pots are in control and capable. It will be given a status of GREEN

Example of detection tools: Hotelling envelopes (2D & 3D); SPC; PCA; CUSUM etc.

If the pot is out of control (ie. abnormalities detected) but the risk of pot failure is low, it is given a status of ORANGE. Root Cause diagnosis and analysis will take place. If a pot with ORANGE status is not attended, there is a risk to turn into RED.

If the pot is out of control (ie. abnormalities detected) but the risk of pot failure is HIGH, it will be highlighted in RED. Root Cause Analysis is required immediately!

The level of risk is assessed based on a set of decision rules.

Once the root cause is identified, Response plan will be implemented to remove the root cause and bring the pot back to in control status. In this case, the pot is given a status of BLUE. A tracking system is activated when abnormality is detected and deactivated when response plan is completed

The chart below is an example of process data for each individual pot are organised for daily monitoring and heat balance review

Decision making guidelines are also embedded for better parameter management.

Human Machine Interface Design

- Simple and Transparent for information presentation
- Directing users' attention to where it is needed
- Incorporating the feedback and learning models
- Guiding the users to monitor the pot condition
- Guiding the users on decision making
- Guiding the users to identify the root cause and implement response plan to remove the root cause

HMI - GUI design examples:

Potline overview

- Pot status for all pots in the whole potline
- Operational events such anode setting etc.

Section overview

- Pot status for all pots in a section
- Feature matching outcome for each pot etc.

FIGURE 12.25 (See color insert.)
Generation 3 Process Control and Management System® developed at the Light Metals Research Centre.

Rob walked out of the potline with Steve and Ford, and headed for the general manager's office. All three had met with the outgoing crew and the incoming one earlier that morning. They had the bones of a plan, with a few gaps, and a lot of faith. Two external groups were pivotal to the new control technology required and to adjusting and controlling the pot heat balance on the sidewall, and, for sure, their services were not free. Trepidation and tension were written like a 5 o'clock shadow on Rob's face.

"We're going to a 'Cash Management' plan meeting, with a request for more cash, Rob. We may need a fire extinguisher for Simcox. He could spontaneously combust." Steve's sense of humor was intact for now.

"We can't run away from it, Steve. Either we face up to this problem, or it's slow death by a thousand cuts. Time we looked the enemy in the eye, I reckon. That's what the guys expect from us." Ford was ready for war.

Rob looked at Ford and smiled. Now he was ready as well.

Exercises

1. Why does electricity dominate the cost of aluminum production? What would the breakdown be for Rob's plant if the electricity usage could be reduced to the amount of energy needed for this smelter's potlines in the case where there was no heat loss at all from inside the pots?
2. What are the possible factors that could prevent the reduction of ACD in the pots by 7 to 8 mm in the present "Breakthrough" project? Name the three factors that you think are most likely and why.
3. Name two possible advanced monitoring techniques that could enable the smelter to track the condition of its pots and intervene before they leave the optimal operating region? What do both techniques require as inputs in order to be successful?

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Answers to Chapter Exercises

Chapter 1

1. Connection between product quality and control of the processes producing the product. Refer to Table 1.1 on typical control failures. Many of these have immediate impact on product quality, volume, delivery to customer. Some control failures cause loss of continuity of production, such as serious accidents, explosions, or fires due to loss of process material containment. Deming's Points 1 and 3 are most relevant to the linkage between the work of people and the quality of the product here

   Point 1: Create constancy of purpose towards improvement of product and service. … and Point 3: Cease dependence on inspection to achieve quality. Both of these principles brings us back to control of the process as the only means to continuously and permanently improve quality.
2. Between 1952 and 2009, there have been 99 accidents at nuclear power stations leading to damage of US$50,000 or more. Most of these accidents have taken place in the United States (56), France (12), and Japan (12). Since Chernobyl in 1986, there have been another 56 accidents. This tells us that achieving good control of complex industrial plants is not a matter only of how much effort or priority is placed on controlling them, since nuclear facilities have the highest priority for control (from List of Nuclear Accidents by Country, Wikipedia).
3. The most useful assumption about industrial production plants is that they are not intrinsically in control or stable. This allows us to take a fresh look at the stability of the process variables and to uncover the real sources of variation, free from the constraints of the causes assumed in the controller design.

Chapter 2

1. The most common control failure outcome is too much crushed bath material arriving at the potlines in the –200 micron-size ranges (referred to as "fines"). These fines are produced through lack of control of the crushing process itself, or through attrition and segregation of the granular bath product in the transportation system to the potlines (e.g., in dense phase piping).
2. Ten out of 11 observations involved people doing work on the floor of the factory—operators and maintainers. Looking at what people are doing in a factory is a good way to find unsafe acts, but also unsafe

conditions, which have originated through unsafe acts. For example, the aluminum dust building up on the spray furnace is caused by lack of housekeeping and, of course, by the design and operation of the metal spray nozzles that lack containment.

3. Build-up of too much bath or alumina on the anode butts in the pots causes a problem in the automated cleaning of this bath from the butts in the rodding room. The net result is often intervention by operators to “assist” the cleaning machine to finish the job on a proportion of the worst anode butts. These interventions should be accompanied by full isolation of the automatic butt cleaning system but occur at quite a high frequency in some plants, exposing people to the risk of unauthorized entry into machines as well as physical interactions with them.

Chapter 3

1. The immediate cause of the HTF tank accident was a build-up of “lights” above the HTF due to the failure of the breather or vent pipe to vent these components from the tank. However, a number of other failures also could have occurred in time, including the reduction of the flash point of the heat transfer fluid due to cracking of the lights over time, and increases to the set point temperature of the HTF due to fouling of the heat exchange surfaces and lack of maintenance. The root cause of the accident specifically was lack of change control in the design of the HTF system, which allowed an unsafe breather pipe system to be installed. However the lack of control of either the HTF properties over time or the heat transfer system itself also are critical to the long-term safety and process stability (temperature of mixing of the anode paste, for example) of the facility.
2. The two defenses in the system are, first, the sampling and testing of the HTF itself for reductions in its flashpoint. This information reveals whether the oil has broken down to a point where it could lead to explosions. The second defense is the monitoring of the overall heat transfer co-efficient for each heating duty, U, which reveals whether the temperature driving force is becoming insufficient to transfer the heat duty, kW, for either heating the pitch or the dry carbon aggregate for the mixing process. Low U should trigger a scheduled maintenance shutdown to clean the fouled heat transfer surfaces in the facility.
3. To a large degree, the fallible decision made by the management some years earlier on this facility was that it could be “set and forget” in terms of its operation. Once this decision was taken, the chance of latent conditions becoming resident in the control of the process was much higher; for example, the lack of use of the two defenses to signal the alarm and the repeated raising of the set point temperature

for the HTF at the furnace. Audits of the control system should have exposed these problems, but the climate or culture of the team was such that audits did not take place, and operator warnings about the system were not heeded.

Chapter 4

1. The following were identified by the Royal Commission:
   a. The failure to identify hazards—no operating HAZOP studies had been conducted. This is point (B) and resulted in the plant manager and the staff not recognizing the risk of low temperature metal embrittlement due to failure of the lean oil system.
   b. The failure of Safety Management audits and of the Incident Reporting System. Point (D)—the natural tendency for loss of compliance with procedures and systems over time, which need to be counteracted by Safety Management Auditing and incident reporting audits.
   c. Failure to report or analyze "process upsets" that were essentially loss of control of the processing of the petroleum coming ashore due to its variability. Point (A), leading to point (E) directly—the failure to report these process upsets in either the Incident Reporting system or elsewhere led to a lack of analysis of why they were occurring or the risks associated with "cold temperature" events. One of these events occurred a month before the final cold temperature event that led to the fatal fire at Longford.
2. The first point above (A) fits into the highest level Loss Control Management Controls because the identification of loss exposures sets the entire framework for the type of organization required. It was found by the Royal Commission that Esso did not have a focus on understanding and reducing process or control problems in their organization, which were actually the biggest risk. The second two points fit into the Management Functions/Tasks box, because the work was simply not done by the management of the plant to ensure that the quality of auditing or the identification and analysis of process upsets were achieved. Control systems were required for these tasks to be done, and design of these systems was the work of senior management.

Chapter 5

1. Machines, methods, measurements, manpower, materials, and environment form the 5Ms and 1E. These are the basic sources of variation in any process.
2. From Table 5.1, low bath level, hard crust at anode setting, high variation in T/AlF3%, and large swings in alumina feed to the pots

(sludge formation) are some of the early signs of low superheat. Triggers for action include pots not maintaining bath level despite bath additions, and anode spikes due to bath freezing (or deformations of the anode surface) under the anodes. This often is combined with signs of low ACD (anode cathode distribution), such as yellow flame and poor anode current distribution.

3. Again referring to Table 5.1, poor feeder hole practices will cause the number of successful searches per day to be reduced, and also a variable number of alumina shots (alumina mass per day) to be observed. The frequency of anode effects will increase, and if certain feeders are accumulating sludge due to the feeder holes being blocked, the duration of anode effects also will increase along with the voltage noise.

Chapter 6

1. Four control loops are present on the diagram in Figure 6.1. Three of these loops depend directly on the cell voltage signal. The three characteristics of this signal are its mean level, which is related in a gross sense to the anode cathode distance (but also to other ohmic and nonohmic voltage drops), its rate of change as alumina is depleted and then added again, and its variation over short periods of time due to noise. In reality, all three characteristics are present all of the time. However the control strategy attempts to reduce the effect of two out of three of the characteristics at any time by selecting time windows when only feeding and not beam movement (ACD [anode current distribution] change) occurs, or allowing beam movement only when the alumina concentration has been adjusted to a reference level. If noise reaches a high threshold level, the measurement of the rate of voltage change with alumina concentration is ceased, and the ACD is increased temporarily. The above mentioned strategy is successful for a narrow range of pot conditions and for a certain proportion of pots that have feeding systems working in an ideal manner. Unfortunately, the strategy is not effective outside these limits.
2. ACD adjust control loop: Cathode voltage drop may be higher than assumed, or anode beam to anode rod voltage drop may be high on some anodes. Even more likely is the possibility that some anodes are not positioned at the correct ACD, and, therefore, that the average ACD does not reflect the mean pot voltage. In all cases, adjusting the ACD is the wrong course of action.

   Alumina Concentration control loop: The change in voltage may be due to a low alumina concentration in only one part of the pot, or the alumina that is fed into the pot may not be reaching the bath or dissolving due to problems with the feeding system or low bath superheat. Rising pot voltage may occur due to reasons not related to the alumina concentration, for example, a change in metal height or in bath height over periods of 10 to 30 minutes, or a reduction in temperature due to addition of cold material, such as frozen bath or even alumina. The controller will misinterpret these signals and possibly move to a higher alumina feed rate as a result.

3. This is a pivotal but difficult question to answer. A good working hypothesis, at least for most of us, is that the performance of staff and management have been measured historically by the production outcomes, and mainly in the short term. The measurement process also has been reactive and biased to negative recognition—a "kick in the backside" when things went wrong. The result of this system is that behaviors that achieve short-term "quotas" or specified outcomes will be reinforced, because management does not look deeper than this. When a measurement process that recognizes improvement (or deterioration) in the stability and capability of the underlying processes is implemented and actually used for staff recognition, it is reasonable to expect that these behaviors (lack of attention to out of control signals) will change.

Chapter 7

1. The number of pots at risk of failure on the potline or one potroom is the control point for this process. If this number becomes greater than five, the potline superintendent should be investigating what specifically are the risks of failure emerging and what can be done to reduce them. Subsequently, the question must be whether to reduce the number of pots at risk by scheduling their removal from circuit over a suitable period of time, which may require a small increase in reconstruction rate for new pots.
2. Six "drill downs" for identifying and also investigating pots at risk of failure include:
    a. Iron concentration in the metal (>0.2%) and possibly the trace metal, e.g., manganese concentration that is in the collector bar steel. Iron indicates a cathode-related problem because the iron can be collector bar related.
    b. Silicon concentration in the metal (>0.05%). This is a sidewall problem usually, associated with corrosion of the silicon carbide bricks due to insufficient ledge protection. This problem is usually related to the operation of the pots and should be addressed by improving their heat balance management so they are no longer at risk of failure.
    c. Red shells—the same as (b) above, but potentially failure is more imminent.

d. Leaking collector bars—can occur due to overheating and leakage of bath at start-up or through later perimeter joint or cathode slot failure. Such leakages can be sealed up and operated with successfully for years afterward as long as the original leakage is documented and monitored regularly (collector bar current distribution) from then onward.
e. High cathode voltage drop or large upward cathode heave—probably indicative of cathode block failure that has resealed itself with frozen bath. Needs to be removed from circuit within a short period (2–3 months) and monitored intensively (iron, cathode current distribution, noise, overheating) until this time.
f. Pots that are prone to high noise, due to a current distribution or magnetic field problem. These pots have an elevated risk of overheating and cathode or sidewall failure. The emphasis should be on keeping them stable in voltage, possibly through higher metal level and higher voltage target.

3. The starting point for management of manufacturing plants is Constancy of Purpose (Deming's Point 1). This is because the work of the staff will always determine success or failure of the product quality. Therefore, the long-term alignment of the staff and the leaders to the purpose is crucial in manufacturing and materials processing organizations. If the purpose is seen to change, that alignment will be lost for a period of time, and, if it changes twice, the alignment may never be regained. It is also the case that some improvement work takes years to complete, and rapid changes in purpose derail these projects. The tactics of the business in achieving its purpose may change often, of course, with external conditions. However, the link between tactics of a business and the underlying constant of its purpose needs to be clear.

Chapter 8

1. Dry fire extinguishing media, such as powder-based extinguishers, are preferred, not only in potlines but also in any electrical and especially high-voltage electrical installations. Any water-based extinguisher carries a very high risk of electrical flashover or arcing across significant potential differences. For example, in a potline, using a fine mist of water near the burning digger would have encouraged current arcing from the potline potential (the digger) to earth (the crane or even the crucible), possibly across 500 V or even higher potential differences.
2. Refer to Figure 8.1 in the chapter, where it is evident that the normal pot temperature distribution overlaps significantly with the hot pot distribution, so that there is a significant risk of detecting a pot

as being hot when it is really part of the normal pot temperature distribution. This reflects a low accuracy of detection of hot pots due to many factors associated with when the temperature measurement was taken in the pot-operating cycle and the accuracy and repeatability/reproducibility of the measurement itself. The danger of responding to a change in a minor proportion of exceptions within a large population, such as "detected hot pots," is, therefore, that this number of detected exceptions might change without there being a change in the true percentage of hot pots. This gives rise to a false alarm.

3. If the process consequences of a failed alarm (say, missing a true change in the number of pots over 975°C) is low, the detection system might be set up to minimize the probability of a false alarm, while tolerating some occurrences of failed alarms. This might be the case if the pot technology tolerated higher pot temperatures better, for example. However, if high temperatures were dangerous for pots in terms of the risk of pot tap out, then failed alarms would need to be minimized while the occasional false alarm might be tolerated. This compromise is avoided in the chapter by the production manager's more intelligent response to the alarm, which is to measure the temperatures again to determine the validity of the original hot pot detections. This response effectively increased the separation "d" between the distributions in Figure 8.1 and reduced both the false alarm (Type 1 error) and the failed alarm (Type 2 error) probabilities. Through checking the past situations of hot pot signals, it is also revealed that the potline superintendents have been responding (with more AlF3 additions) mainly to false alarms in the past.

Chapter 9

1. The three considerations are (1) the sources and stability of the variation in the process (including how much of it is understood), (2) the process constraints within which it can operate optimally, and (3) the natural variation that can be accepted (and not responded to) on the basis of the first two considerations.
2. The two control elements that need to be reformulated to achieve the new operating envelope are the control objective and the control mechanism. The reason why this reformulation is necessary is that the present control objective and mechanism used in most control systems assume that the cause of the variation is known and that further investigation of cause is not required.
3. The three questions include: What is my job? How am I doing? What is my future? The first two questions relate to the design of

people's work and the specification and measurement of the control point for each process and task. The feedback of this information in real time is the basal level of an effective control system in a production environment; for example, the feedback of the anode setting accuracy of a crew during the same shift as the anodes were set.

Chapter 10

1. Anode effects initiate under one or more anodes, indicating that the cause is low alumina concentration under these anodes rather than generally across the whole pot. Reducing anode effects, therefore, requires that no single region or anode is left short of alumina supply, because this will cause an anode effect to initiate there. The effect of sludge buildup in a pot is usually to increase a higher alumina concentration in a particular part of the pot because sludge buildup always occurs locally, not globally across the whole pot. Therefore, the areas remote from sludge buildup tend to become depleted in alumina first, creating the potential for local anode effects in these regions and on/off anode effect phenomena, as observed in some very large pot technologies (350 kA – 400 kA).
2. The five steps to an organized workplace are described as 5S and are, in order of application: Sort, Set in order, Shine, Standardize, and Sustain. In Figure 10.1 these are written as Organization (meaning, sorting out what must be kept and what must be thrown away), Orderliness (a place for everything and everything in its place), Cleanliness (of equipment and workplace), Standardization, and Discipline (as in having the discipline to sustain the first four over a long period of time). This rather simplistic description of 5S doesn't describe the systemic means to achieving each S. However, the reference handbook *5S for Operators: Five Pillars of the Visual Workplace* (Productivity Press, 1996), quoted in chapter 10, gives excellent practical advice on how to implement 5S.
3. The visual appearance of the equipment or machines is often the crucial first indicator of a problem that requires maintenance. However, a dirty machine will hide most of the signs, such as leaks in process fluids, missing fixings, or loose moving parts. The act of cleaning equipment also draws the attention of the person doing the cleaning to these tell-tale signs. The "Shine" step of 5S, therefore, must be in place in order to detect these first signs of maintenance requirements. Other condition-based signals, such as vibration monitoring, unusual sounds from rotating equipment, rapid use of oil, etc., are also of great importance.

Chapter 11

1. The four balances are enthalpy (sensible and latent heat), electrical current flow, alumina, and bath materials balances (liquid phase). The alumina balance causes the greatest impact on the electrical balance through increasing resistance to current flow vertically through the metal. This gives rise to disruption in the enthalpy balance.
2. For example, in Dairy Processing, investigating empty tank contents when milk quality variation increases and checking heat exchanger effectiveness well before loss of temperature specification in the product. These control actions will improve the process. Not monitoring the emptying or refilling of tanks and not including the checking of exchangers in maintenance PMs will degrade the process.
3. Myopic discounting behavior is observed, for example, when people cut short conversations or longer-term improvement tasks to get "instant gratification" through an action or recognition of action. In particular, short-term actions that address symptoms, or make a problem "go away" for a while, even though the reasons for it arising are not being tackled. In myopic accounting, the need for certainty and a fast result overrides the greater benefits of longer-term improvement.

Chapter 12

1. Electricity cost dominates the production cost because half of the energy used produces heat rather than aluminum.

   The specific energy consumption is 14.1 DC kW/kg at this smelter, and this gives an electricity cost per month of $27 million. This cost is directly proportional to the power usage that varies directly with pot voltage. Assume the line amperage and the number of pots in circuit remain constant. Also assume that the theoretical kWh/kg for aluminum production is 6.5 kWh/kg—the enthalpy for the pot reaction, which would be used in the case of zero heat losses. In practice, this value could not be reached, however, because the current would still need to be driven through the bus bars external to the pots, and this energy, therefore, would be lost. Thus, assume that the voltage loss in the external bus bars totals 0.30 V per pot, at the existing line amperage. The pot voltage is, therefore, $V = 6.5 \times 93/298 + 0.30 = 2.03 + 0.30 = 2.33\text{V}$. This means the actual energy consumption is $2.33 \times 298/93 = 7.47$ kWh/kg. Energy costs, therefore, reduce to $27 million × 7.47/14.1 = $14.3 million per month.

2. The factors that could cause this ACD reduction to be abandoned include:
   a. Cooling of the pot until the bath is no longer able to achieve alumina dissolution at the required rate, followed by sludge buildup and voltage instabilities.
   b. Loss of bath superheat until large crust thickness and ledge growth prevent anode setting or make it too difficult in the pot corners.
   c. Small problems, such as a mis-set anode or a blocked feeder hole cause anode spikes or multiple anode effects on too many pots through a potline, overwhelming the resources of the operators to fix them and producing many sick pots.
   d. Immediate overheating of the pot due to the anodes being too close to the metal pad, giving instant back reaction and short circuiting problems.

   Of these factors, the first three (a to c) are more likely in the present circumstances—either heat imbalance driven or due to loss of "safety margin" for recovering from operational disturbances. This is an observation made at many smelters operating in the 4.0 – 4.5 V range and is due to both operational imprecision and lack of an advanced automatic control mechanism.
3. Both Hoteleling T^2 multivariate envelopes and principal component monitoring can be used to track the progress of pots through their normal process state and detect signs of divergence from this state. However, both techniques need a set of process variable inputs that are the *precursors of process disturbance* rather than the consequences of those disturbances or the delayed process outcomes, such as temperature or bath composition. This means the alumina feeding process and the electrical current balance must be targeted for use by these monitoring systems.

Glossary

Aluminum Smelting Terms

AE, AE Freq.: AE is the abbreviation for anode effect, a rapid rise in pot voltage that occurs when the bath under some or all anodes becomes too low in dissolved alumina. AE Freq. is the frequency of anode effects per pot in the potline. Along with the duration of each AE, the AE Freq. drives the generation of perfluorocarbons, which are powerful greenhouse gases. Elimination of AEs is always a key environmental goal for smelters.

Aggregate: The dry coke and butts mix that is then mixed with pitch to bind it before forming into anodes.

Airburn: This refers to oxidation of the anodes by air and occurs when the anode surface temperature exceeds 400°C and is not protected from air by the anode cover. Anode covering is, therefore, a critical operation for maintaining the anodes with each pot.

AlF3, XS AlF3%: Aluminum fluoride is the main additive to the cryolite-based bath, and is usually referred to as a mass percentage in the bath in excess of the cryolite stoichiometry, XS AlF3%. AlF3 is added in batch additions to the bath in order to maintain a certain target level of XS AlF3%.

Alumina, alumina conc.: Alumina is the main raw material for smelters and is added to each pot at an average rate of 1.90–1.93 × the rate of aluminum production. This rate is directly proportional to the electrical current through Faraday's law. Alumina concentration (conc.) is measured nonroutinely in the bath as a mass percentage.

Anode: Carbon anode for smelting pot 20 to 50 are used per pot depending on size of pot. The anodes are the positively charged electrodes in the pot, and reduction of the oxide containing ions to carbon dioxide gas occurs there. This reaction consumes or "burns" the anode over a period of 20 to 30 days, depending on the current density.

Anode butt, or butt: Used anode, burned away until only a butt is left. Recycled to the rodding room for reprocessing of the carbon and the anode rod.

Anode bake, or bake: Anode baking furnace for heat treating the anodes to 1100–1175°C in pits between gas firing flue walls.

Anode poles: Pieces of rough cut timber or saplings that are used in the potline to terminate anode effects that have not been terminated automatically.

Bath: Molten electrolyte in pots is cryolite-based, with additives like AlF3.

Burnoff: When an anode separates from the rod, this is called a burnoff. These are very serious events for a pot and can lead to open circuit on the potline.

Butt cleaner: The machine that cleans the butts of the remaining crust and bath after they have been removed from the pots.

Butt/thimble press: A rodding room machine that removes the butts and the cast iron thimbles from the anode rod, prior to its recycling to the casting station where another anode is mated to the rod.

Carbon plant: The part of a smelter where the anodes are produced, baked, and cast into the anode rods.

Casthouse: The part of a smelter where the molten aluminum is solidified (cast) into shapes such as ingots for remelt by customers, or billets for extrusion, or block for rolling into sheet or foil.

Cathode: The negatively charged electrode in the pot, which also forms the "floor" of the pot on which molten aluminum builds up as it is produced. There are a number of cathode blocks fitted together (usually sealed with rammed carbon paste) into the floor of each pot.

Center passage: In a potline, there are passageways for hot metal and anodes at either the center of the line (splitting one half of the two rooms from the other half) or at the one third and two thirds positions for longer potlines.

Coke: Calcined petroleum coke is used to make carbon anodes for smelters, because this coke has high purity and low ash content.

Collector bars: These are cast into the cathode blocks in the pot and transfer the electrical current out of the pot to the cathode bus bar and on to the next pot.

Cryolite: Sodium cryolite is usually referred to as simply "cryolite" and is the basis for the bath. It is an ionic salt with the formula Na_3AlF_6 and is composed of 3NaF for each AlF3. This salt dissociates when molten into AlF_x complexes.

Cryolite ratio, CR: This is another way to characterize the content of AlF3 in the bath. CR is the molar ratio of NaF/AlF3, in the bath, and corresponds to a given AlF3%. A commonly used form of the CR is the mass ratio of NaF/AlF3, and this is known as "Bath Ratio" or BR. Due to the molecular weights of NaF (42) and AlF3 (84), the BR is exactly half of the molar ratio, CR.

Current density: Usually refers to the anode current density, and is the amperes of current that would flow through every square centimeter of anode bottom surface when the anodes are all new. In practice, the anodes are partially consumed, and the operating current density is higher than that quoted for a pot technology.

Cut out (of a pot): Refers to a pot that is being removed from the electrical circuit of the potline. This is performed before the pot actually "taps out," which means the loss of molten bath and metal through a hole in the pot. A potline cut out also can occur in extreme circumstances, usually when there is insufficient electrical power available or the economics of the production process warrant ceasing production.

Cut out wedges, wedge gaps: On multiple riser pot technologies, each riser may be short circuited using a copper wedge that is inserted into a preformed gap between the cathode bus of the upstream pot and the cathode bus of the pot being cut out of circuit. When it is necessary to cut out a pot, the wedges are inserted into these wedge gaps after the gap surfaces first have been cleaned.

Duct: Refers to the duct on each pot that withdraws a large volume of air and pot fume from inside the superstructure of the pot. This gas is transported to the dry scrubbing process, or Gas Treatment Center (GTC), for removal of the hydrogen fluoride gas generated in the pots, along with dust and condensed fume. The duct gas flow rate from each pot and the temperature of the gas are both important for environmental and heat balance control of the pot.

Dust: Carbon dust that collects in the bath in pots and must be removed.

End-to-end pots: In older potline technologies, before overhead robotic cranes were available, the pots were arranged so that they could be serviced exclusively from the operating floor.

Fe%: The percentage of iron in the molten aluminum in a pot.

Forming, forming stops: Refers to the process of anode forming by vibrocompacting of the paste in a mold box. Forming is a batch process that operates stably when the paste and the mold box stay at the equilibrium temperature; in other words, when there are no stoppages due to equipment problems and a long run of green anodes can be produced consecutively.

Green carbon plant: The plant where the anode coke, pitch, and crushed butts are mixed together to form unbaked (green) anodes, prior to their heat treatment in anode baking furnaces.

Green paste: The mixed carbon and pitch aggregate that is formed into anodes.

Green scrap: Mass percentage of green paste that has to be scrapped instead of formed into anodes, due to shutdowns of the Green Carbon plant.

Green stack: The stocks of green anodes that are available to be baked.

Hammer mill circuits: Hammer or impact crushers use a sequence of hammers and screens to crush and size hard materials. These circuits can produce excessive fine particles, especially if there is a growing recycle of oversize particles.

HTF tank: Heat transfer fluid (HTF) system for heating plant raw materials, such as coal tar pitch in this case.

Load, off-load: The electrical current for the potline is known as load, or being on "full load." Conversely the potline is off-load when the current is zero, or on half-load when it is 50% of the nominal current.

Metal: Usually refers to molten aluminum in a pot.

Miss: An anode setting "miss" means not to set anodes for a day, thereby extending the anode rotation by a day or even two days. This means the anodes currently in the pots must survive for this extra time, compared to be normal anode rotation (24–32 days).

NaF: Sodium fluoride is the other main component of the cryolite-based bath.

Noise: Variation in pot voltage over the short term (usually amplitude of variation over a 60-second period) is characterized as a mV or micro-ohm amplitude that is then averaged over five-minute periods and eventually over whole days, so that the short-term, high-noise periods are averaged out of the data. Time on noise control (minutes in a day), therefore, is a better measure of how noisy a pot, or potline, is.

Number 4 chain: One of the power and free conveyers in the rodding room, bringing anodes to/from the potroom, using small conveying cars on a powered drive chain that loops around the rodding room to the potroom.

Pitch: Coal tar pitch is used as the binder for the coke and butts fractions that make up an anode. This pitch needs to be heated and sometimes also melted in order to liquefy it and bring it to the correct temperature for mixing with the solid carbon fractions.

Pot: The electrolysis unit in the potline where the molten aluminum is produced. Each unit is completely separate in its production process, but the pots are joined via the electrical current supplied in series by the potline bus bar. Pots are the source of value in the smelter. Also known as a "cell."

PM: Preventative maintenance session.

PTM: Pot tending machine: A bridge crane with semiautomated functions to service modern pots with anodes, beam raising, metal tapping, anode cover addition, crust breaking, cavity cleaning.

Rod, rod repair: The anode rod and steel anode yoke and stubs are sometimes damaged by contact with bath through failure of the anode or through very high current draw or high anode cover level on the anode.

Rodding room: The facility where the anode rods are connected to the anodes and where the anode butts are returned for cleaning and reprocessing.

RT: Two-way radio transmitter, within the smelter.

Setting: Replacement of the spent anode butt(s) in each pot is called "anode setting," or just "setting." This is the most critical of pot operations because the cleanliness of the cathode and the accuracy of the anode position above the metal surface depends upon how well the new anode is set.

Si%: The percentage of silicon in the molten aluminum within a pot.

Sidewall: Pots have sidewalls to contain the bath and metal inventories for the electrolysis process. If the sidewall loses its protective frozen layer of cryolite, the wall itself is quickly eroded at up to 1 mm per day for carbon walls leading to extreme temperatures of the wall (500°C on the steel potshell) and failure by tap out of bath or metal through the wall.

SP: Controller set point, e.g., temperature set point for the HTF controller.

Stub to carbon: This is a critical component of the voltage drop through the anode. The stubs or "pins" of the anode assembly are cast into the stub holes formed into the anode using molten cast iron in the rodding room.

Superheat: The elevation of the bath temperature above its primary crystallization (liquidus) temperature.

Tapping, tappers: Metal removal from each pot is known as the "tapping operation." The operators who do this work are sometimes called "tappers," although in modern organizations the operator or process technician is able to carry out the full range of pot operations.

Tap hole: The hole broken in the crust of a pot so that the tapping pipe can be inserted for removal of molten aluminum.

Tap hole breaker: A separate pneumatically driven point breaker for opening the tap hole. May be retrofitted onto the breaker bar of an existing pot technology in order to remove manual work in opening the tap hole.

Temperature: Unless otherwise stated, this refers to the temperature of the bath in a pot.

Upstream: The electrical current (+ve) flows from upstream pots to downstream, effectively from higher positive potential on the potline to lower positive potential.

USC: Unscheduled anode change that occurs due to a failure of anode. This requires its removal and replacement in the pot ahead of its scheduled replacement time.

Voltage: Unless otherwise stated, this refers to the voltage across a pot in the potline and is measured on every pot from the anode bus bar to the cathodic bus bars that collect the current from the cathodes in the pot.

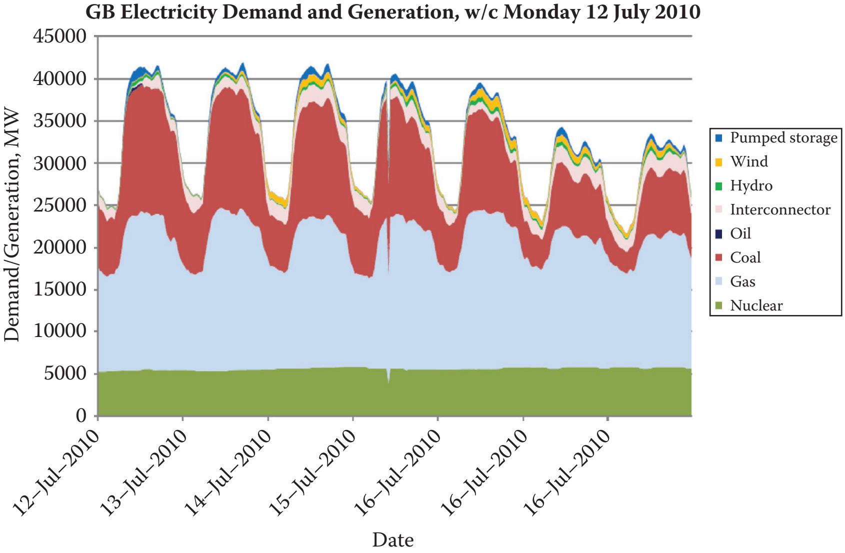


FIGURE 1.1
Variation in total power demand and generation during one week in 2010. (Adapted from GB electricity demand variation, pp. 49–53, GB Electricity demand variation—2010 Football World Cup, *Energy Trends*, September 2010, Department of Energy and Climate Change, United Kingdom.)

FIGURE 2.1
Anode cover material overflowing the anode yokes and collapsing due to its high internal temperature exceeding the phase change temperature of the crust.

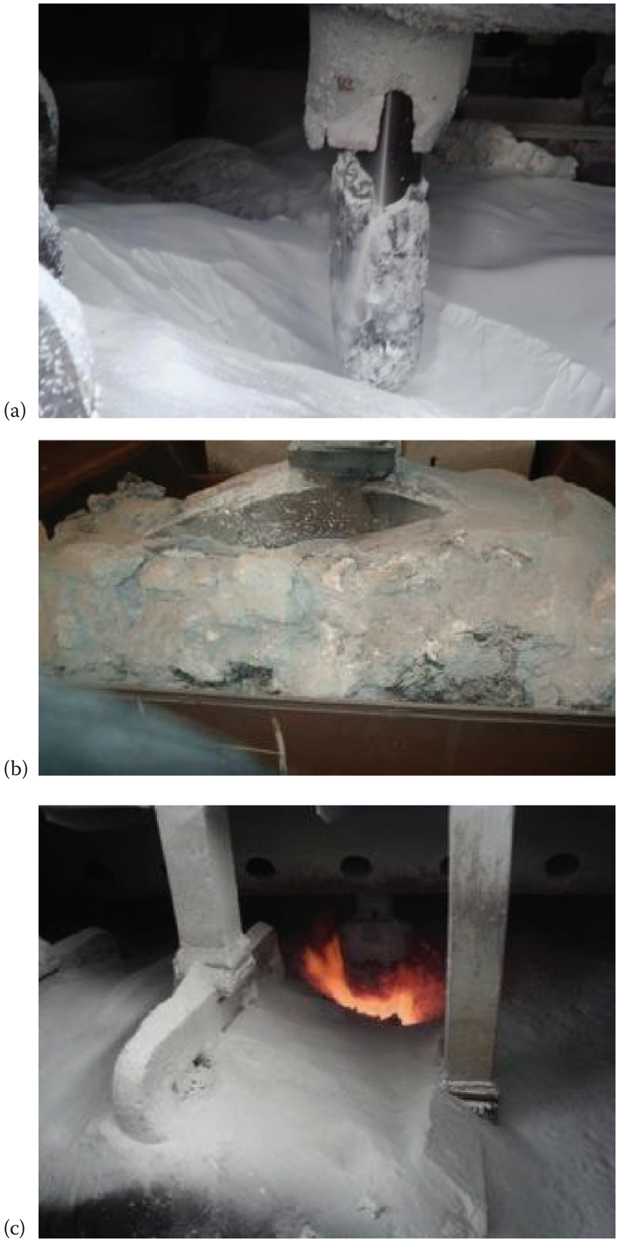


FIGURE 2.3
a-c Three photographs of high amperage pots in which the alumina is being fed partially onto the cover and anodes, rather than into the bath, through problems in the alumina feeding systems.

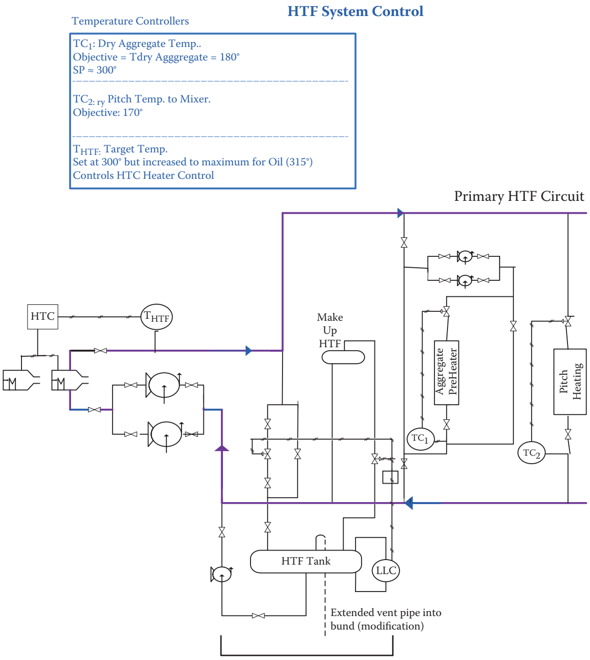


FIGURE 3.2
Main schematic of the HTF system.

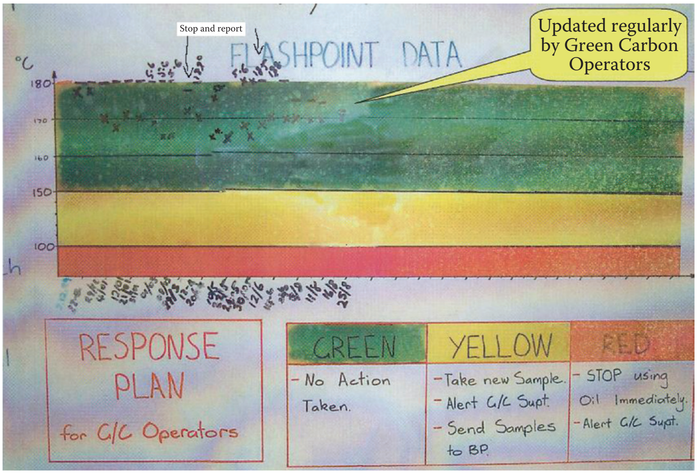


FIGURE 3.4
The precontrol chart of HTF flash point data, with the response plan for operators of the green carbon plant below the chart. (Courtesy of New Zealand Aluminium Smelters, Tiwai Point, New Zealand.)

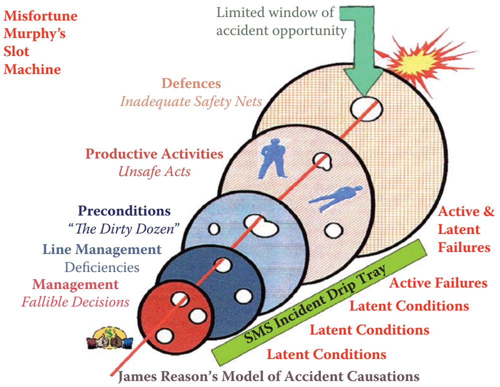


FIGURE 3.5
The Swiss cheese model for accident causation. (Adapted from the G. Dupont modification of Murphy's slot machine (diagram originally by James Reason). Online at: www.system-safety.com/train ingvideos/Traini ng_Aids/Misfort ue%20Murphy/misfort une_murphy.htm)

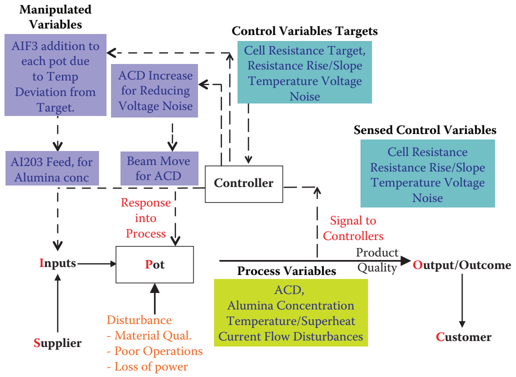


FIGURE 6.1
Basal automated control loops and process variables for a smelting pot.

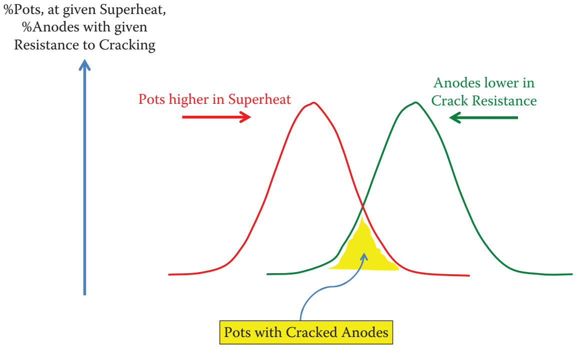


FIGURE 6.2
Effect of variation in potline superheat and anode cracking resistance. (Courtesy of Barry Sadler, who crafted the illustration one day on a whiteboard.)

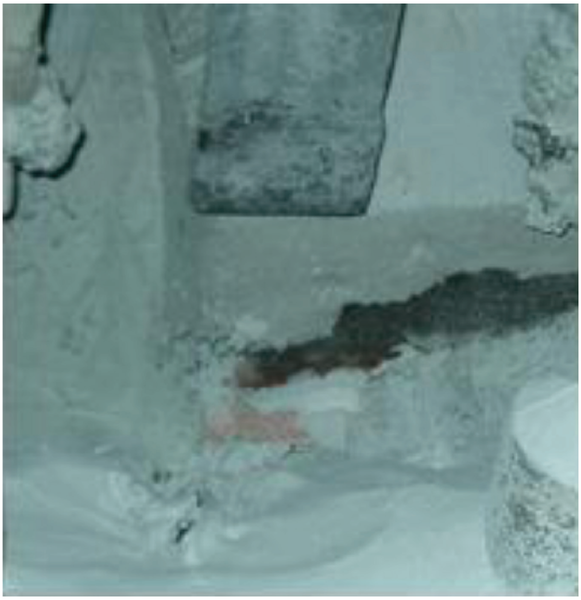


FIGURE 6.3
The start of anode airburn near the bath surface and on the corner of the anode near its slot with the adjacent anode.

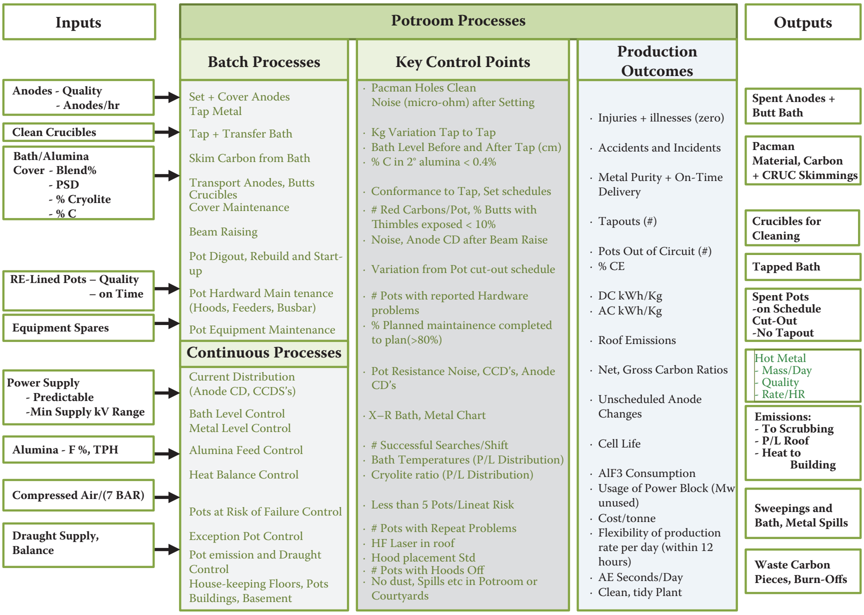


FIGURE 7.3
Potroom process flow chart showing the key processes and their control points for the production of aluminum.

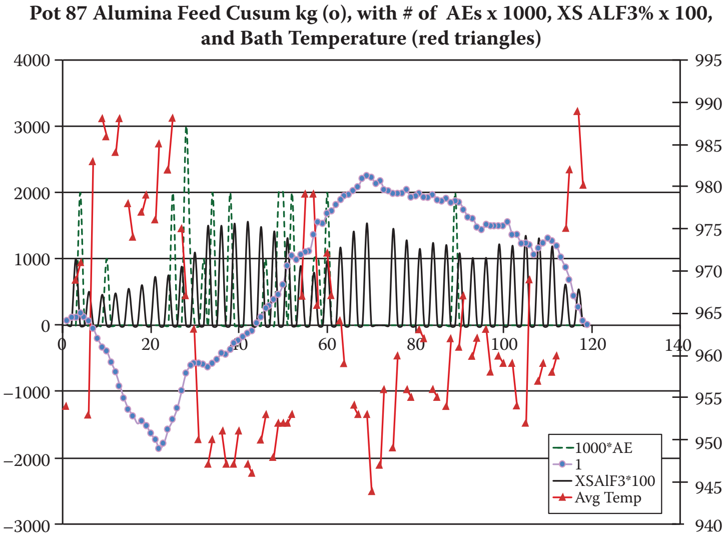


FIGURE 9.3
Example of alumina feeding imbalances driving pot heat balance for a point fed 220 kA pot, over a 120-day period.

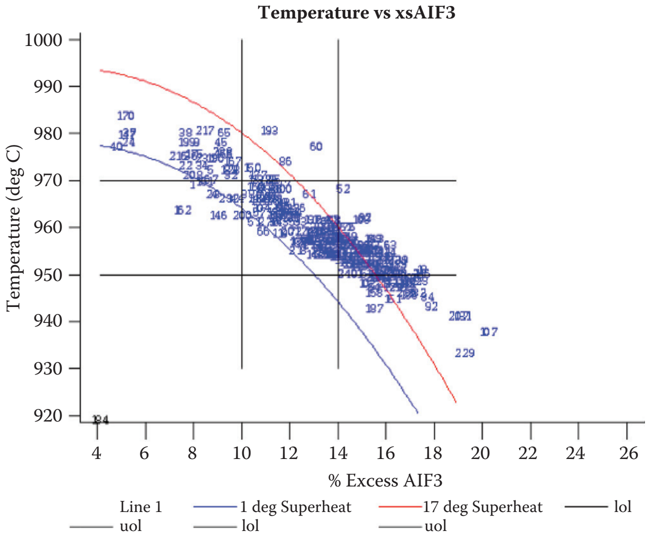


FIGURE 9.4
Bath temperature/ALF3% concentration slice of the pot operating window, showing real data from one potroom. In this case, the lines of constant calculated superheat are 1°C and 17°C, but the percentage of pots in this range is still only 55% because the univariate controller responds to the temperature and XS AlF3% variables separately (the control box shown) without consideration of the dependency between them.

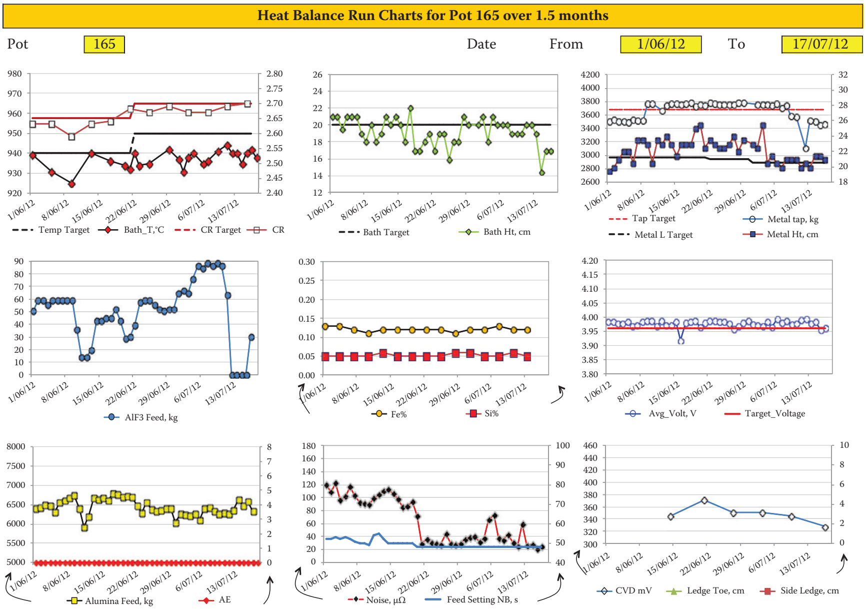


FIGURE 11.1
Periodic Heat Balance Review charts for pot 165.

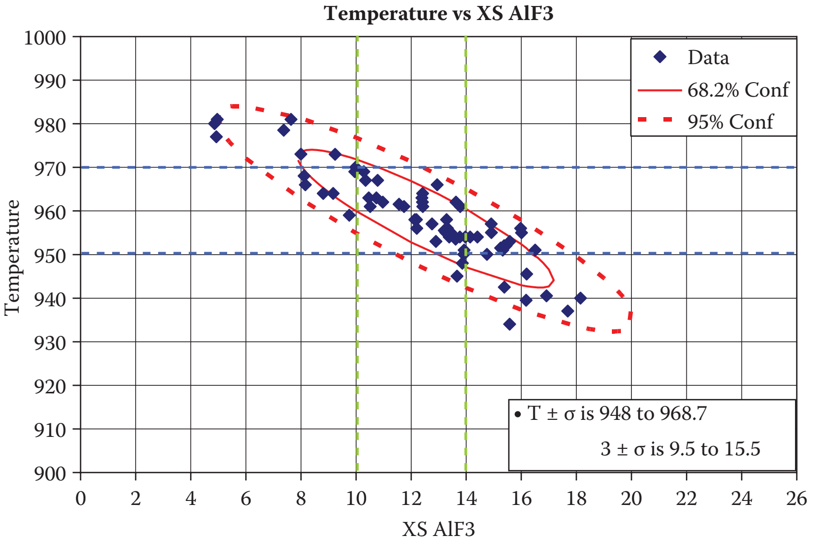


FIGURE 12.6
Plot of temperature versus XS AlF_3 with the control or confidence ellipses.

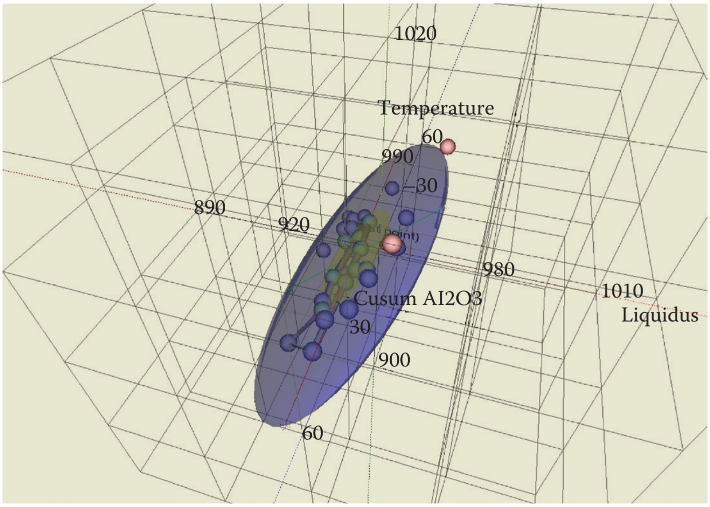
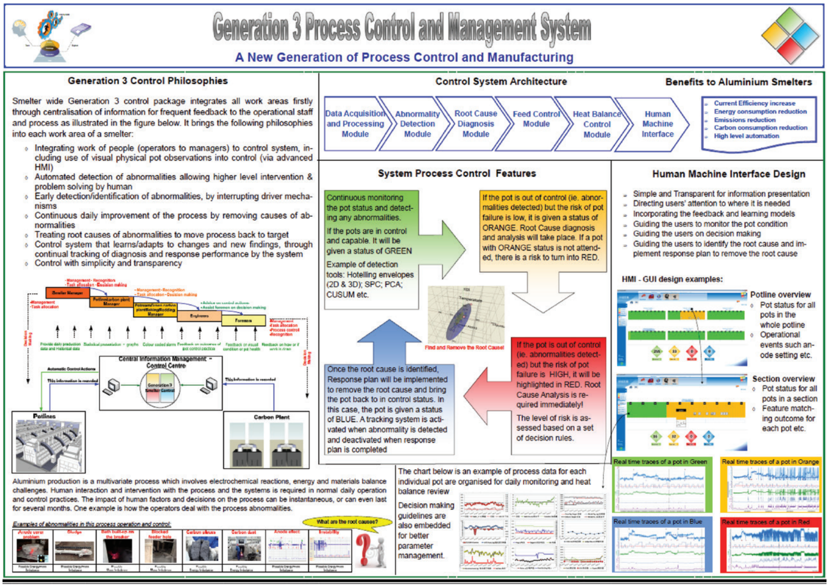


FIGURE 12.9
3D pot operating envelope by Hotelling statistic at 95% confidence, using bath temperature, liquidus temperature, and alumina feed rate (represented by its CuSum).



Generation 3 Process Control and Management System

A New Generation of Process Control and Manufacturing

Generation 3 Control Philosophies

Smelter wide Generation 3 control package integrates all work areas firstly through centralisation of information for frequent feedback to the operational staff and process as illustrated in the figure below. It brings the following philosophies into each work area of a smelter:

- Integrating work of people (operators to managers) to control system, including use of visual physical pot observations into control (via advanced HMI)
- Automated detection of abnormalities allowing higher level intervention & problem solving by human
- Early detection/identification of abnormalities, by interrupting driver mechanisms
- Continuous daily improvement of the process by removing causes of abnormalities
- Treating root causes of abnormalities to move process back to target
- Control system that learns/adapts to changes and new findings, through continual tracking of diagnosis and response performance by the system
- Control with simplicity and transparency

Aluminium production is a multivariate process which involves electrochemical reactions, energy and materials balance challenges. Human interaction and intervention with the process and the systems is required in normal daily operation and control practices. The impact of human factors and decisions on the process can be instantaneous, or can even last for several months. One example is how the operators deal with the process abnormalities.

Examples of abnormalities in this process operation and control:

Control System Architecture

Data Acquisition and Processing Module → Abnormality Detection Module → Root Cause Diagnosis Module → Feed Control Module → Heat Balance Control Module → Human Machine Interface

Benefits to Aluminium Smelters

- Current Efficiency increase
- Energy consumption reduction
- Emissions reduction
- Carbon consumption reduction
- High level automation

System Process Control Features

Continuous monitoring the pot status and detecting any abnormalities.

If the pots are in control and capable. It will be given a status of GREEN

Example of detection tools: Hotelling envelopes (2D & 3D); SPC; PCA; CUSUM etc.

If the pot is out of control (ie. abnormalities detected) but the risk of pot failure is low, it is given a status of ORANGE. Root Cause diagnosis and analysis will take place. If a pot with ORANGE status is not attended, there is a risk to turn into RED.

If the pot is out of control (ie. abnormalities detected) but the risk of pot failure is HIGH, it will be highlighted in RED. Root Cause Analysis is required immediately!

The level of risk is assessed based on a set of decision rules.

Once the root cause is identified, Response plan will be implemented to remove the root cause and bring the pot back to in control status. In this case, the pot is given a status of BLUE. A tracking system is activated when abnormality is detected and deactivated when response plan is completed

The chart below is an example of process data for each individual pot are organised for daily monitoring and heat balance review

Decision making guidelines are also embedded for better parameter management.

Human Machine Interface Design

- Simple and Transparent for information presentation
- Directing users' attention to where it is needed
- Incorporating the feedback and learning models
- Guiding the users to monitor the pot condition
- Guiding the users on decision making
- Guiding the users to identify the root cause and implement response plan to remove the root cause

HMI - GUI design examples:

Potline overview
- Pot status for all pots in the whole potline
- Operational events such anode setting etc.

Section overview
- Pot status for all pots in a section
- Feature matching outcome for each pot etc.

Real time traces of a pot in Green

Real time traces of a pot in Orange

Real time traces of a pot in Blue

Real time traces of a pot in Red

FIGURE 12.25
Generation 3 Process Control and Management System® developed at the Light Metals Research Centre.

Materials Science

CONTROL for ALUMINUM PRODUCTION and OTHER PROCESSING INDUSTRIES

Mark P. Taylor
John J. J. Chen
Brent Richmond Young

"Everyone interested in potline operation, from crew member to general manager to researcher, could benefit from this book."

—Mark Cooksey, CSIRO, Australia

An uncomfortable observation in the shift logs and process control records of most aluminum smelting plants is that process control failures, large and small, happen every day. Although only a small fraction of these failures give rise to catastrophic events, the difference between a disaster we read about and a failure which, although expensive, has no irreversible consequences, is only chance.

Control for Aluminum Production and Other Processing Industries exemplifies new control thinking fused with an understanding of process variability, and how to diagnose abnormalities and their causes in aluminum production plants. Many real-life examples in the book demonstrate the importance of human behavior and a scientific, questioning approach in the control of a technologically complex process. Written from the perspective of production staff and management, the book also gives readers a view into the human aspects of accidents and their analogy to failures in control of production.

Production plants regularly experience more control failures than successes and staff must continuously strive to establish stability and control of their process. Through on-the-job experiences of the authors and their industry colleagues, the control experiences described in this book provide readers with a foundation for building their own robust control rationale and a framework for avoidance of plant control problems.

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