

From smokestack to high-tech: the changing face of paper science and technology during the last 50 years

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Vast changes in outlook, science, engineering, and even the craft of papermaking have taken place since 1940.

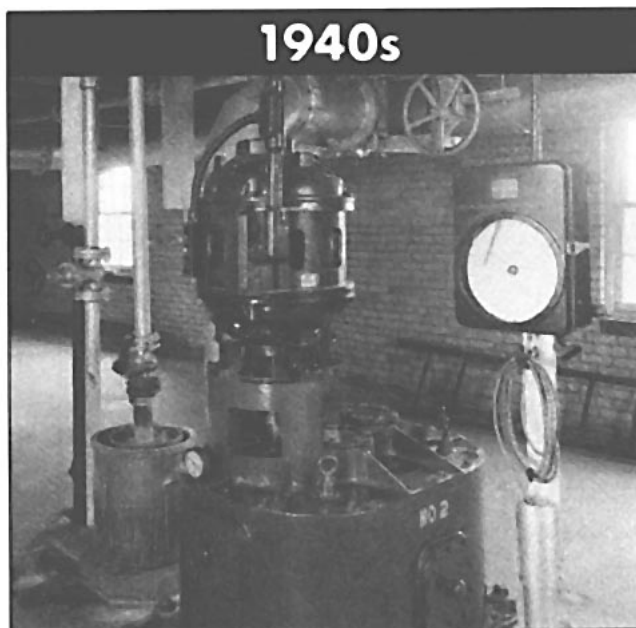
Cultural changes due to external forces

Organizations, like organisms, respond to external forces by adapting or perishing. Powerful social and ideological forces caused radical changes in the culture and philosophy of the paper industry over the last 50 years. I believe the following changes are the most significant.

Research

World War II, in the early '40s, demonstrated the need for and value of scientific research and organized development for military and industrial supremacy. By the end of the '40s all industry, including mature industries like pulp and paper, were completely (and mostly newly) indoctrinated with the dogma that research was essential for growth and success. New research laboratories and centers were created intra- and extra-murally. Young, bright, highly educated persons were aggressively recruited both at home and abroad. Universities and academics became objects of frequent visits and monetary support. These activities increased at a great rate, which, by the early '60s, was obviously not sustainable in the long run. In a speech I gave in 1963 or 1964, I calculated that if the annual rate prevailing at the time for the increase in the research effort of the United States continued into the late '90s not only would every man and woman be doing research, but babies would have to be drafted as well. Thus, research expenditures and efforts leveled off after that, but not before effecting major and lasting changes in the way our industry carried out its functions. Here are some examples.

Funds became available for more precise, sophisticated and costly instruments. Statistical analyses of data became routine. These led to deeper understanding of the properties of paper and of factors affecting them. In short, "paper physics" was born, with a worldwide constituency routinely using not only precise dynamic methods for studying paper mechanics but lasers, ultraviolet and infrared spectrometers, nuclear magnetic resonance



spectrometry, and advanced forms of chromatography to study other properties.

New mathematical techniques were explored. Old conjectures and speculations were subjected to mathematical analyses. For example, it was known as a matter of observation that table rolls induced suctions. But not till the '50s was the suction measured and analyzed, first algebraically and then by a differential integral equation. These studies led to the present universal use of foils. Similarly, the problem of multicylinder drying was mathematically transformed into differential equations in the '50s. Indeed, 1956 saw not only the first attempt of using a digital electronic computer to solve a paper drying problem but the first time a "what if" experiment was carried out inside a computer instead of directly on a paper machine dryer. Today, the whole of a pulping line or a paper machine is routinely modeled mathematically in computers.

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Processes became legitimate and much pursued objects of in-depth research and developments in the laboratory and at pilot-plant and full scales. This in turn led to finer and more automatic controls, which culminated in universal use of on-line testing by very sophisticated instruments coupled to computer controls. Standard deviations of paper properties have been significantly reduced with attendant reliability in use.

The aggressive recruitment of young scientists and engineers from the outside world made it possible for ideas born outside more easily to penetrate and be assimilated by our industry. Tissue culture of trees and the molecular engineering performed on their DNA are examples. Percolation theory, an esoteric mathematical theory used in the study of electrical networks, was used as a connecting link to unify two theories on the mechanical properties of paper. The most advanced theories and practices of metallurgy are being routinely incorporated in the design and use of equipment under corrosive or other hostile environments in our processes.

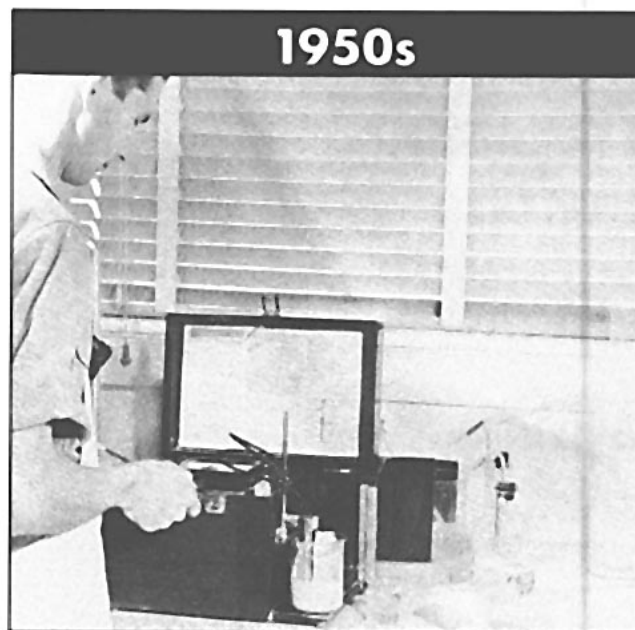
The environment

Perhaps in no other sector has the culture and philosophy of the industry changed so much as in the accepted dogmas concerning the environment. In the early '40s, it was the accepted axiom that industry was necessarily accompanied by bad odors (the smell of money), soot and fly ash on the surrounding village, town, or countryside, colored and putrid streams and canals, and other assorted pollutions. Today, after much heart-searching and several billion dollars later, our attitude is different. The best example is the story of dioxin. It was only in 1986 that it became possible to analyze for certain dioxins in parts per trillion. We then discovered that some paper products did contain dioxins in these ultra minute quantities. The industry immediately went to work to determine sources, reactions, and amounts of these materials in various products and effluents, and in less than three years developed ways to minimize them. These solutions were openly published and many millions of dollars were appropriated to implement them. This is, in my judgment, a fine example of a responsive and civilized approach to a social problem.

International forces

From its birth until the 1960s, the U.S. paper industry had its eyes turned inward to the home market. There was, of course, an export trade in pulp, paper, and board. There were also joint ventures of U.S. corporations with enterprises of Europe or of other countries. But these were secondary in their magnitudes and influence on pulp and paper manufacture and marketing in the United States. Then the oil crisis of 1973 hit. There were almost immediate technological responses, especially in the management of energy by the industry. In less than a decade, the use of petroleum oils was cut by 40%, and the industry increased its cogeneration activities, burning black liquor, bark, and waste wood and chips for more than 50% of its needs. These activities involved massive retrofitting of boilers and furnaces and great concentration on efficiencies in energy use. Total investments amounted to many millions of dollars.

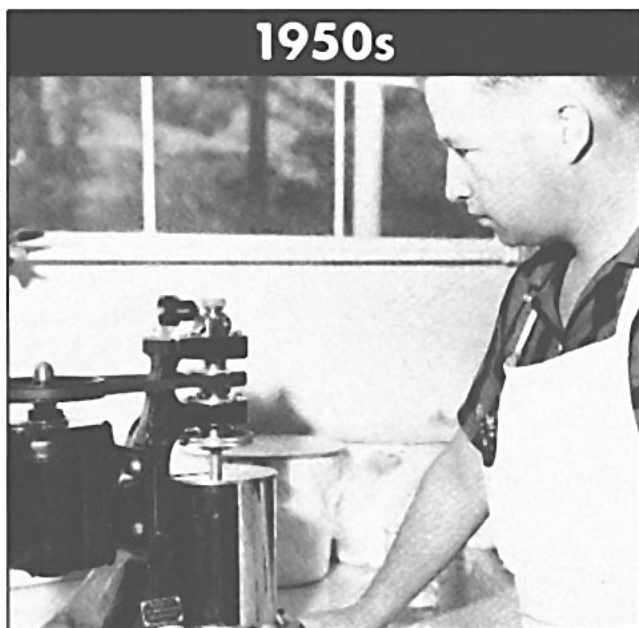
The late '70s and early '80s brought on inflation, followed



by a deep recession, followed by a large influx of foreign funds to fill the void created by federal budget deficits. The net result was a steep rise in the value of the U.S. dollar. The direct effects were, of course, in the marketplace: exports died down while imports from Europe, Japan, and other countries rose steeply. Among the indirect effects was, again, a change in attitude and technological advances in the paper industry.

The change of attitude has been described by the infelicitous expression "the globalization of the paper industry." This refers to the realization by the industry of the need to enter the world markets more aggressively and systematically. As a result, many more companies than before studied and served the export market. The American Paper Institute surveyed the industry in 1989 and found a steady increase over the last decade in the number of companies that earned more than 10% of their incomes from exports to foreign lands.

The technological advances resulting from the strong dollar in the mid '80s came about because the increase in the share of the American home market by foreign exporters to the United States was not in the commodity sectors but in the highest-value-added sectors—and hence the highest-quality products. Thus, the response of the U.S. paper industry, if it was to increase its own exports as well as regain some parts of the home market, was to intensify its own efforts to produce products of the highest levels and uniformity of quality. New heights in smoothness, brightness, overall printability quality criteria, and mechanical properties of coated bleached board and fine papers were attained with, even more importantly, better control of and smaller variances in these qualities. Statistical process and quality control paradigms became the central and universal concerns of paper manufacturers. This, in turn, led to on-line testing by more accurate and sophisticated instruments and fine tuning of process variables by modern computer-aided protocols.



Changes in specific fields

Let us now look at what happened specifically in different fields of pulp and paper, starting with the forest.

The forest

The greatest single change in pulp and papermaking of the last 50 years, emanating from the forest, was the successful introduction of hardwoods as a major source of raw materials. As late as 1947, when I entered the paper industry completely innocent of its ancient lore, I was taught by an authority that birch trees and other hardwoods were weed trees in the paper forests of softwoods. To be sure, with clear cutting some hardwoods entered mills, but this was only by the accident of being there, and they were used only as a filler. Today, millions of tons of paper of excellent optical and printing quality and consisting predominantly, or even entirely, of hardwood furnishes are produced every year. Now the exotic plantations of eucalyptus trees in Brazil and other tropical or subtropical countries appears to usher even greater, and more differentiated, use of hardwoods.

Of equal importance was the continuous development of scientific control and long-term management of softwood plantations. By analyzing soils of different sites and correcting them for macro and micro nutrients, careful selection and planting of seedlings, well thought out liberation of the seedlings from surrounding unwanted growths followed by planned thinnings at optimum periods, the modern well-managed softwood forest yields many times the yield of the natural forest of the same species on the same site.

Tree genetics has advanced significantly, and superior trees have been successfully bred with good growth rates, straighter shapes, smaller and more efficient crowns, and greater resistance to disease and insects. The prospects are before us of even greater values to be obtained from tissue and single-cell cultures to produce clones of superior and even molecularly engineered trees.

I see only one negative development of late. Forestry research has followed a tradition of open cooperative and free interchange not only of ideas but even of superior seeds and seedlings. I believe the allure of future values of tissue culture and similar research incline their practitioners to follow the more restrictive proprietary research of other fields. This is natural, logical, and fully justified in competitive research serving a free enterprise market. But I am not sure that in this particular field we have as yet reached the "competitive" stage where secrecy is imperative, or whether we are still in the "basic" research stage where the open clash of contrary ideas is still the determinant of successful research.

Pulp manufacture

One of the greatest innovations in mechanical pulping was the successful development of refiner mechanical pulping. This development not only gave pulps with a good combination of properties at economical costs but led in turn to the unique properties of thermomechanical pulp, which can be used either for its own contribution to the final properties of paper made with it or to displace chemical pulp (of about half the yield on wood) from newsprint manufacture while allowing the web to leave the couch at high speed and go through the presses without rupture. Thermomechanical pulp, in turn, has led to the development of chemithermomechanical pulp, which is brighter and better bonding at a cost of only some 5% loss in yield. I believe this innovation may well lead to the much desired "high yield, high brightness, high strength" pulp, or what I have called the "90-90-9" pulp (90% yield, 90% brightness, 9-km breaking length). If such a pulp can be made with a nonreverting brightness, in effect, it will double the yield of the forest in terms of tons of bright, strong pulp per acre when compared with current chemical pulps.

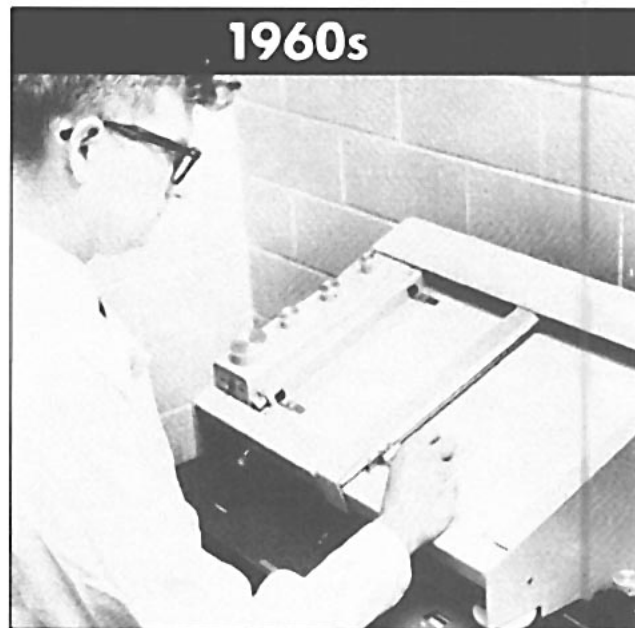
At the beginning of the period under review, kraft pulping was establishing its rise to dominance in the chemical pulp markets due to two successful developments: the Tomlinson recovery furnace and the perfection of multistage bleaching, particularly the sequence incorporating chlorine dioxide, CEDED. By now, that dominating status is well nigh complete due to innovations in batch digesters (e.g., cold blow, computer controlled programs of cooking, stainless steel cladding) and the full development of continuous cooking by the Kamyr systems of single and multiple vessels. The discovery that the addition of anthraquinone to a kraft cook, in quantities less than 0.1% on wood, increases both the yield and the rate of cooking further strengthened the hold of kraft cooking. This innovation is of particular value when the pulp mill is limited in its total production of pulp by the size of the recovery furnace; it allows the manager to increase his production by 2-4% at the same rate of black liquor burning. The use of totally enclosed and well ducted drum or diffusion washers and the trials of different forms of extended delignification plants to greatly lower kappa numbers promise to solve environmental problems associated with reduced-sulfur-based cooking and with chlorine-stage bleaching, thus continuing the reign of kraft pulps. But, of course, other approaches—using solvents or enzymes, for example—are challenging this dominance. Nothing but good can come from such competition.

Similarly, there is a growing challenge to the use of chlorine in the first stage of bleaching, with possibilities of its substitution by chlorine dioxide or by oxygen or its derivatives. But novel ways have already been found to continue the use of Cl_2 , without the production of chlorinated dioxins and furans. There still remain the challenges of other halogenated organics to the use of chlorine. As a result, there is a strong rear-guard defensive and offensive research into the minute details of bleaching chemistry. This intense activity may well prove to be one of the great legacies the period under review will leave to the science and technology of bleached pulps.

An interesting innovation in bleaching was based on what originally was a curious observation of almost purely academic interest. It had been observed that above a certain critical Reynolds number the friction factor of a pulp slurry dropped down to that of the suspending medium, flowing by itself at the same rate. On this basis was built a high-shear mixing pump, which fluidized high-consistency pulp suspensions thoroughly and enabled the intimate and uniform atomization of gases like chlorine dioxide or chlorine and the mixing of them with the pulp in C and D stages of bleaching.

An "invisible" innovation of the period under review was the introduction of the use of exotic metals like titanium and various alloys of steel and of special polymeric materials into the corrosive and erosive environments of pulping, bleaching, and chemical recovery equipment. In many of these uses, the materials are at the edge of metallurgical and material sciences and technologies.

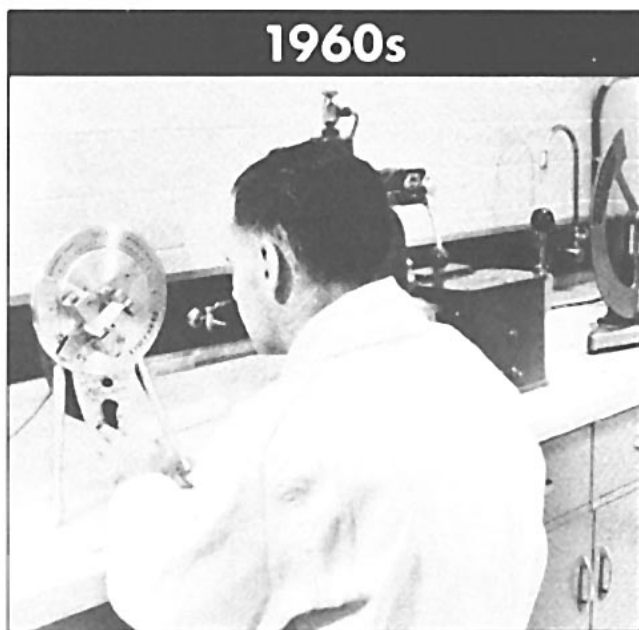
Another truth which was instilled into my mind when I joined our industry was "Paper is made in the beater." That was because it was true that the final properties of the paper were radically and irreversibly changed as the pulp was beaten and also because we still used "beaters" or hollanders. A major development of the last 50 years has been that of the disc refiners, which not only relegated "beaters" to the history books—aside from pulp testing laboratories using Valley beaters—but has dominated all refining practices. Thus, huge disc refiners (using more than 25,000 hp each) are used to disintegrate raw chips into mechanical pulp or in hot-stock refining of semichemical pulps, and for secondary refining of all sorts of furnish from the coarsest to the most delicate, slender, and fine fibers. But here is a paradox: We still do not know how the fiber gets refined. A look at the flows—primary, secondary, and tertiary—indicates patterns and regions of the most complex type, suggesting that the flows are what is now designated technically as "chaos." Indeed, the last time I looked into what was going on inside a refiner, the complex patterns of flow brought to my mind Dante's warning at the gates of the Inferno: "Abandon hope, all ye who enter here." Thus, we have no rigorous theory based on first principles to describe the action of the refiner other than descriptions of complicated phenomena occurring in the grooves which appear to prepare the fibers to be refined between the bars as flocs stapled on the bars' edges. So here is a major challenge for fluid mechanics specialists in the coming years. Fortunately, practice has outpaced theory, and during the last 50 years disc refiners have been run and controlled to give desired qualities of the most diverse types with reasonable understanding of how to increase efficiencies, or control bonding versus cutting



tendencies, based mostly on sound empirical research with a modicum of theoretical analysis. Full understanding of the mechanics of flow and of fiber modifications inside a disc refiner awaits a giant in fluid and solid mechanics and mathematics to be interested in the chaos existing therein.

Paper manufacture

The many changes brought to the paper machine over the last 50 years have a common feature amongst them: a change in paradigm. This change was to apply basic principles of engineering science to the various operations involved. The paper machine was divided conceptually into a series of unit processes and each was analyzed for stability, efficiency, and uniformity of conditions both in the machine direction (MD) and cross-machine direction (CD). Analysis of pressure dissipation at the inlet resulted in the now universal adoption of tapered inlets to the headbox. Concepts of intensity and scale of turbulence led to various designs of energy dissipation devices—bunches of small-diameter pipes in parallel, sudden expansions, holey rolls, plastic sheets in converging flows—which deflocced the stock and stabilized velocities both in MD and CD. Exotic phrases like "Taylor-" and "Goetler-vortices" appeared in the wet-end literature to explain the appearance of strange disturbances on the wire—"worms"—and to eliminate them. As speed increased the large open "swimming pool" headboxes with perforated baffles and zigzag passages, almost arbitrarily placed by their designers and builders, were closed, and air pressure was used as a pad to hasten the flow. This in turn gave rise to studies of automatic control of total pressure as well as of the head of stock and the pressure of the air in the headbox. Finally, the hydraulic headbox, with its smooth inside and precisely controlled turbulence level, arose. In short, the headbox and its slice were transformed from a rough-and-ready contraption of 50 years ago into a finely tuned, precisely designed device controlled to give uniform and steady flow at about three to five times the speeds of yesteryear.



Similarly, engineering science was brought in to understand the events taking place on the fourdrinier—all machines (other than vat machines for board) used single-wire fourdrinier. It was a matter of observation that table rolls caused suction in the diverging section of the nip, but it was not till the '50s that this suction was quantitatively analyzed, first geometrically and algebraically and then by a differential-integral equation, and its genesis and behavior truly understood. This gave rise to the use of foils to control two-sidedness and uniformity of the sheet. Studies of dynamic forces due to roll suction also elucidated a certain type of instability on the wire, because of the geometry arising from the wire wrapping around the roll, and directions were given to avoid them. In the meantime, studies also were going on in academia on the drainage and permeability of compressible pads of fibers to explain the mechanics of sheet formation and the steep increases in resistance to flow experienced near the middle and end of the wire. It was almost inevitable that bright and adventurous spirits would invent the twin-wire systems to overcome this handicap and avoid two-sidedness—first in the design of the Inverform and later by many other designs. This also shortened the wet end, providing economic advantages in mill construction. Finally, designs were created for high-consistency forming with very ingenious energy dissipation construction to defloc the stock in the headbox. Such designs would further shorten the wet end and reduce operational costs, but it is still a design to be perfected in the coming decades.

At the same time, studies on the functions of the “wire” brought about a major change to the “fabric.” This change, in a sense, is a reversion to the drainage device of Monsieur Robert and his excellency Ts'ai Lun, who used cloth some one and a half and 19 centuries before, respectively. But the modern fabric is made of late-20th century synthetic polymer monofilaments for a long, very arduous life, uniquely woven to give an open structure for easy draining and cleaning, and with good fiber support indices to enhance retention and reduce wiremarks. Thus, the

modern forming section—with its sleek, short, streamlined headbox, its foils and centrifugal forces to drain two sides of the web in twin-wire formers using fabrics and running at high speeds on very wide machines—bears only a superficial resemblance to the systems of 50 years ago.

At the same time as these changes were wrought, scientific research on the wet press was going on, and the phenomenon of rewetting was discovered. Other researchers made obvious the need for a reservoir for the copious quantities of water to be pressed out at the high speeds being contemplated. This realization led to several ingenious inventions: the fabric press, the Venta-nip press, and the blind drilled holes behind the felts. Ultimately, the dwell-time in the nip had to be under direct, positive control and extended beyond what soft rolls or cushioning felts could provide, and the extended-nip press became a successful innovation. At the same time, just as the fabric replaced the wire on the drainage elements, wet press felts of unique designs, combining weaving with other processes of the textile industry, came in satisfying profusion to offer long life, easy open drainage, easy cleaning, and fine cushion action in supporting the delicate and often very thin webs running at several thousand feet per minute. Changes in the dryer section came along two paths:

1. Improved efficiency
2. More uniform CD profile.

To improve the efficiency of drying, the process was analyzed in terms of first principles of heat and mass transfer. In 1957, for the first time, the problem of drying multicylinder dryer sections was solved on a primitive electronic digital computer, and a paper machine was so modeled and subjected to a “what if” sort of experiment on a computer. In the meantime, actual experiments on small-scale and full-scale dryers elucidated the regimes of flow of condensates inside dryers—puddling, cascading, and, finally, rimming. Both calculations and observation of heat transfer emphasized the need for precise control of the siphons. Finally, rods were installed axially inside cylinders to yield significant increases in heat transfer.

To improve uniformity of drying, the dryer section was enclosed within well designed, quick opening hoods. Cross ventilation schemes, with concomitant changes in dryer felt designs to give good permeability to air flows, followed naturally. Finally, the high speeds of modern machines making low-basis-weight paper resulted in the serpentine single-dryer felts wrapping over top and bottom dryers successively to eliminate fluttering and breaking of the web. (Recent developments are tending to eliminate the second tier of dryers.)

As precision of control of the paper web on high-speed machines improved, it became possible and desirable to put sophisticated size-press and coating systems on-line. At first, various sequences and designs of rolls were used for these purposes. But ultimately the blade coater, with different types of heads, was perfected to give an extremely smooth, scratch free surface with excellent printability characteristics. The fluid mechanics of the coater head has now become amenable to numerical analysis by large, high-speed computers, and it reveals regions of secondary flow to be eliminated and of chaotic flows inviting further analyses and studies.

Two major innovations were introduced into machine

calendering, in addition to numerous incremental improvements in design and use. These were (a) the hydraulically controlled flexible shell of the "swimming" rolls resting on a stationary beam, which can be used to give precise control of the crowning of the roll as service conditions demand, and (b) the soft-roll calender, which performs some of the functions of the supercalender on-line. Large diameter, highly polished Yankee dryers and other forms of gloss calenders and dryers have been introduced, again to finish the surface of the web on-line.

Work on computer control of paper machines started in the '50s but came into general use in the '60s. Now the control of moisture, basis weight, and caliper in the machine direction is fairly commonplace. (Similarly, in the pulp mill, protocols for kappa number control and of bleaching process parameters is fairly common.) New sensors for on-line measurement—and eventual control—of other properties such as the various dynamic moduli of paper and of optical properties and of CD control are in active development.

Finishing of paper

The finishing of papers and its conversion from rolls to sheets was a highly labor-intensive operation 50 years ago. Major changes have taken place in these operations both to automate the various steps required and to attain higher precision of dimensions and uniformity of properties. Numerically controlled automatic slitting, with roll changing on the fly, is now in fairly common use. Similarly, the automatic inspection for dirt, creases, holes, and other flaws in the sheet and sorting of the sheets into accepted and rejected streams after precise slitting and cutting, and finally stacking the sheets into products of exact dimensions has resulted in two major savings:

1. A drastically reduced labor force
2. The elimination of the need to guillotine the sides with attendant considerable savings of first-class paper.

Although it is not generally considered a "finishing" process because it is mostly practiced on-line when the web has about 30% moisture, I consider the Clupak process one of the most innovative processes in paper modifications of the last 50 years. By compacting the sheet under pressure into its own plane at moisture contents of 30% and then drying the web and hence effecting bonding, the paper gains controlled large increments in its stretch-to-break with a minor loss in stiffness and breaking load. Consequently, the toughness of the sheet (i.e., its resistance to shock loads) is considerably enhanced. Hence, three sheets of Clupak-treated paper will do the work of four sheets of the same basis weight without such treatment when these sheets are converted into multiwall sacks; this amounts to nearly 25% savings in materials.

Paper science and technology

In discussing changes in pulp and papermaking, we already have seen some of the many changes which came about in the fields of science and technology. For example, we have noted the intensive studies in tree genetics, culminating in tissue- and single-cell cultures of clones of trees. These studies are at the tip of advances of the science of botany and of biotechnology.

It may be fairly said that "paper physics" was born and nurtured during the last 50 years. To be sure, some scientific studies of paper properties and some application of physics to understanding and controlling paper properties and processes have always been used. But the last 50 years saw, for the first time, concerted, systematic application of the principles of solid mechanics, rheology, optics, and electrodynamics to elucidating the properties and behavior of paper.

Similarly, engineering science, with application of the principles and methods of fluid dynamics, heat transfer, mass transfer, control theory, and modeling whole processes or even a whole pulp or paper mill numerically in a computer, has been introduced and nurtured to maturity in these 50 years. Lack of knowledge of these applications and methods of engineering science would preclude any real understanding of the complexities of modern pulp and paper technologies.

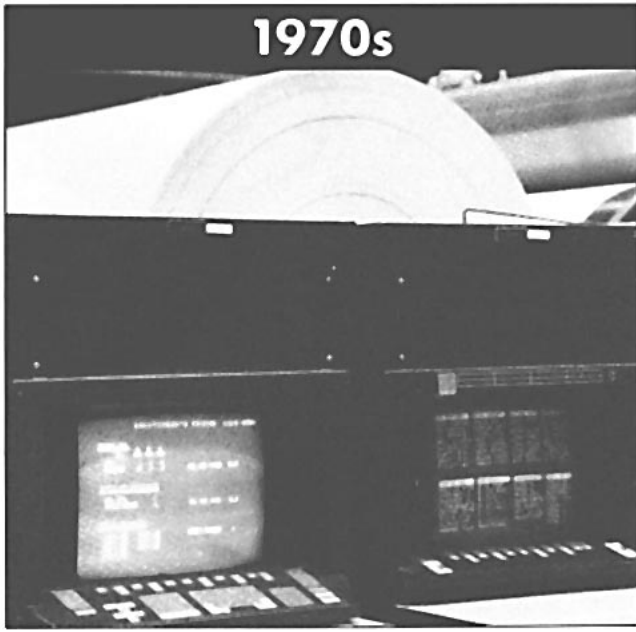
Overview and summary

How do we summarize these vast changes in outlook, in the science, engineering, and even the craft of making pulp and paper? I believe in the saying "from smokestack to high-tech." Of course, "smokestack" and "high-tech" are only labels. Labels tend to have emotional contents, hidden meanings. But I mean by them the category of manufacture using old, unchanging mechanisms and processes on the one hand and manufacture moving with the advances in physics, chemistry, biology, and other natural sciences and utilizing their latest relevant discoveries on the other. I believe the introduction in the last 50 years of systematic studies, and diligent application of, the findings of the following sciences categorize pulp and paper as "high-tech."

- Genetics and tissue culture
- Manufacturing of paper and board free from certain undesirable impurity compounds to a few parts per trillion
- Hydrodynamics of the wet end
- The minute and very complex details of events in "impulse drying"
- The substantial body of theoretical and experimental studies of paper as "an engineering material"—its statistical geometry, its bonding, its properties and behavior
- The great progress in the theory and practice of advanced control of our processes to truly remarkable, narrow tolerances.

The people behind the changes

The reader by now will have noticed two types of omission in my chronicles of the past 50 years. The first is due to inadvertence or ignorance on my part and relates to the many innovations made but not mentioned here, e.g., developments in machine drives, in computer-controlled wrapping, labeling and dispatching of paper rolls, and many others. These omissions reflect personal bias and limitations on my part.



The other major and, this time, willful omission was in not naming and paying homage to the innovators behind the innovations. I was asked to name these outstanding scientists and engineers, but I demurred for a very serious reason. To do proper justice in allocating credits for innovations requires a meticulously careful study of patents and publications and archival research of other sources of information. If such work is not done most carefully, persistently, and objectively, there arises the hazard of unjust and injudicious attributions. Even if I were given the time necessary for such research, I am not a specialist in archival research and hence begged to be excused from the task.

However, the reader who wishes to trace, in a general way, the development of any of the changes discussed has a simple road to follow. Just look up the subject in the annual indices of *Tappi Journal*. In the majority of such searches, the development will appear in reasonable completeness and will take the reader back to the source, or sources, because almost all the innovators in paper science and technology of the last 50 years were members of TAPPI. They contributed to *Tappi Journal* the fruits of their intense and creative work in series of papers and lectures. You will find their names in the list of recipients of the TAPPI Gold Medal, now known as the Gunnar Nicholson Gold Medal Award, and the R&D and other divisional awards of TAPPI. Their work was recognized as worthy, and TAPPI honors them. Indeed, one of the major contributions of the last 50 years to paper science and technology was the growth of TAPPI and similar technical associations of the paper industry in various countries. In this respect, these bodies of scientists and engineers, and TAPPI in particular, have been the principal engines for change in paper science and engineering.□