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Preservation of Paper Based Materials: Present and Future Research and Developments in the Paper Industry

Introduction

The essential nature of paper[1] has changed very little since its invention in China in A.D. 105. It consists of cellulose fibers suspended in water and formed into a matted sheet on screens.

While handmade paper methods have changed little over the centuries, the modern machinemade paper is a very complex, and highly capital-intensive mix of craft, science and engineering.

Cellulose is a naturally occurring polymer, that is a long chain-like molelcule made up of a large number of smaller (monomer) units. In the case of cellulose, the monomer units are anhydro-glucose molecules. The number of units in a cellulose molecule (known as the degree of polymerization or DP) varies with the source and treatment of the material. Cotton and flax cellulose have approximately 7,000 to 12,000 units while cellulose derived from refined wood pulp which has been chemically separated from the lignin binder in wood and bleached have about 2000 to 3000 monomer units per cellulose molecule.

Cellulose occurs in fibrous form. The fibers are made up of both regular, ordered crystalline regions and irregular, less dense amorphous regions. The flexibility and ability to absorb moisture derive from the amorphous regions.

The beating of cellulose fibers in water develops microfibril fuzz on their surface which causes the fibers to stick together when the formed sheet of paper is dried.

Paper made with only cellulose fiber acts like a blotter. It absorbs water readily, swelling in the process. Ink tends to feather on such paper. To overcome this, papermakers add a size to the paper in order to make it more resistant to fluids. The amount of size needed depends on the printing process. Offset printing, which is now the most widely used process for books, requires more than other printing methods.

Filler materials or loadings are added to paper pulp to increase opacity and ink receptivity. Fillers such as clay, calcium carbonate, titanium dioxide, or other white pigments, while they keep the printing from showing through the other side, do nothing for the strength of the paper but in fact detract from it by interfering with fiber-to-fiber bonding. Printing and book papers are often coated with a composition containing a white pigment and an adhesive such as starch or casein in order to improve brightness, surface smoothness, and printing quality. Colors and a wide range of other additives are often added for special purposes.

A Brief Historical Overview

From the beginning, sources of good quality cellulose were inadequate to the demand. The search for cheaper and more plentiful sources is one of the continuing themes in the history of papermaking.[2] In early days, clean white cotton and linen rags were the principal source of cellulose.

The machines such as the hollander, developed to speed the pulping process, replaced beating with grinding action with a resulting shortening of the fibers produced.

The discovery of chlorine by Scheele in 1774 and the recognition of its bleaching properties allowed colored and dirty rags to be used in addition to clean white ones. Unfortunately, the bleaching process degrades the fiber.

Early papermakers sized their paper by dipping the paper in dilute solution of gelatin. The introduction of alum-rosin size and its rapid adoption by almost all papermakers was the next major setback to paper quality. In 1807 Moritz Friedrick Illig found that rosin soap could be added to the beaten fiber suspension and precipitated by adding alum. The paper made from this mixture became sized in the same step as the sheet formation and only required drying, thus eliminating an extra dipping and drying step. From the point of view of the paper manufacturer this was a marvelous advance and alum has been considered the papermaker's cure-all up to the present. From the librarian/archivist's and conservator's perspective this was the greatest in a series of calamities to befall on the process of papermaking.

The quest for other sources of cellulose led to the discovery that wood cellulose could be used to produce acceptable paper. Wood cellulose fiber is bonded together by lignin. When wood is ground mechanically to produce paper, the lignin and other wood byproducts such as hemicelluloses are left in the finished product. The result is a low-grade, relatively weak and chemically unstable paper such as that used in newsprint.

Processes were developed during the nineteenth and twentieth centuries to treat wood pulp chemically to remove lignin and other impurities. These treatments are harsh and degrade the cellulose fiber in the process; however, bleached chemical pulps are stronger and more stable than paper made from groundwood (mechanical) pulp or from semichemical pulps, though not as strong as rag fibers.

Paper permanence began to decline sharply at about the time wood pulp was displacing rags as the main source of fiber. This has caused many people to think that high-quality, permanent paper can only be made from rags and that paper made from rags is necessarily better than that made from wood pulp. This has been shown not to be the case. In fact, it has been determined that the major cause for the decline in permanence was the introduction of alum, which just happened more or less to coincide with the transition to wood fibers.

While the chemical pulping and bleaching of wood fibers is certainly responsible for a decrease in the polymer chain length and a lower strength in the paper, the decrease with time of whatever strength the paper had when new is less attributed to these treatments and can be explained primarily by two synergistic chemical processes which attack the paper over time—acid catalyzed hydrolysis of the cellulose polymer linking bond, and oxidation. There are, in addition to these, a host of other degradation processes to which paper is susceptible.

Causes of Paper Degradation and Current Research

William K. Wilson and E.J. Parks in a detailed examination of aging of paper list the following reactions which might occur during the natural aging of paper:

(a) hydrolysis;
(b) oxidation;
(c) crosslinking;
(d) changes in order, or crystallinity, due to changes in moisture content;
(e) photolysis;
(f) photosensitization;
(g) photo-oxidation.[3]

The study of the chemical reactions in paper is difficult. One can measure changes in physical properties, but attributing these effects to specific reactions is not something that can always be done with a high degree of certainty. More than one reaction is likely to be occurring and these often interact.

Accelerated Aging Methods

The processes which degrade paper are relatively slow at room temperature. Even poor-quality paper will last for twenty-five years. Raising the temperature increases the rate of these processes so they can be conveniently studied in the laboratory in a reasonable time period. Special aging ovens with very good temperature and humidity controls are employed. The practical range of temperatures which can be used to give measurable rates of degradation is from about 70° to 100°C. After aging, loss of strength is commonly determined by use of standard tests. The most commonly used is the TAPPI MIT Folding Endurance Test. A 1.5 cm.-wide strip of paper under 1 kilogram (or, in some laboratories, 0.5 kilogram) of tension is folded repeatedly through an angle of 270° until it breaks. The required number of folds is taken as a measure of the paper's strength. By measuring the degradation of samples of a paper over the 70-100° range it is possible to extrapolate to room temperature to predict the useful life of the paper under normal storage conditions. These tests show that seventy-two hours at 100°C is equivalent to about twenty-five years at room temperature. Other tests that are frequently used measure tensile strength and extensibility, tearing strength, and light reflectance.

The accelerated aging approach has been used for several years and much of the research on longevity of paper is based on such experiments. Comparisons with long-term aging experiments has shown it to be a viable method of studying paper aging.[4]

Hydrolysis

Cellulose is fairly stable in neutral and alkaline media but is readily hydrolyzed in acid, the rate increasing with hydrogen ion activity (decreasing pH). This acid catalyzed hydrolysis results in cleavage of the monomer to monomer bond, thus fragmenting the polymer chain and weakening the paper. The presence of oxidized groups in the cellulose causes it to be more readily hydrolyzed. Acid hydrolysis takes place in the amorphous regions of the cellulose fiber. The cellulose chains, once broken, tend to crystallize making them more brittle. The fibers are weakened but the fiber-to-fiber bond is affected less seriously. New paper tears by pulling apart the fiber-to-fiber bonds giving a fuzzy tear; aged, degraded paper tears by fracture of the fibers giving a clean tear.

The principal source of acid in book paper is alum. Up until very recently almost all book papers contained alum rosin size and much of this paper has a pH of 4.5 or less. Such paper has a useful life of twenty-five to fifty years. Another important source of acid is pollutants in the air, particularly sulfur dioxide and oxides of nitrogen. The presence of trace metals (iron, copper, manganese) in the paper play a role in this by catalyzing the oxidation of sulfur dioxide to sulfur trioxide which, with water, produces sulfuric acid.

Chlorinated compounds such as residues from chlorine bleaches can generate hydrochloric acid.

Some of the products of paper oxidation are acidic.

Deacidification is becoming a well-established practice though research continues. Researchers at the National Archives are studying liquid phase deacidification with methyl magnesium carbonate looking at ways to improve this process. Research at the Library of Congress on gas phase deacidification with diethyl zinc is progressing to final pilot testing in a 5000 book per charge chamber. There is reason to expect this method will move soon from research to practical implementation.

Oxidation

Cellulose and especially other organic constituents of paper are susceptible to slow reaction with atmospheric oxygen. The reaction produces peroxides which decompose and promote further oxidation. The oxidation is catalyzed by metal ions such as copper, cobalt, manganese and iron, and ozone in polluted air acts as a strong oxidizing agent. Copper sulfate is sometimes used as a slimicide. It should not be used in the manufacture of permanent paper. Hypochlorite and chlorine bleaches leave the cellulose more susceptible to oxidation.

The relative importance of hydrolysis and oxidation to the degradation of paper varies with the kind of paper and environmental conditions, but both are important. For alkaline papers oxidation is the major mode of degradation.

One of the criticisms of some of the accelerated aging tests is that it is a gross measure which doesn't provide information about how the paper is degrading. Some recent work at Carnegie-Mellon Institute Research[5] has addressed the question of the relative importance of oxygen-dependent and oxygen-independent deterioration. The relative importance of these two processes was found to depend on the moisture content, the type of paper, the temperature, and the physical property monitored. They found that oxygen-dependent deterioration is more important for newsprint than for rag paper. Yellowing was caused primarily by oxidation; tensile strength loss was caused primarily by oxygen-independent reactions. In all cases, both processes contribute significantly to the deterioration.

The atmospheric oxidation process was found to be inhibited by a decrease in acidity. This means that alkaline paper will not only prevent hydrolysis, but will offer some protection against oxidation as well.

Chemiluminescence Studies

Some recent research conducted at Battelle Columbus Laboratories[6] used the very weak chemiluminescence (light produced as a result of a chemical reaction at environmental temperatures) accompanying the degradation of paper. The author introduced this technique to Battelle when he worked there as a research chemist in the late 1960s. The light emission which accompanies the degradation of a wide range of organic materials is, where the detailed mechanism has been determined, associated with the oxidation of the materials. It seems reasonable to assume that the chemiluminescence observed from paper is due to oxidative degradation but this has not been determined.

Though there have been some long-term studies which support the validity of accelerated aging methods, there have been some concerns about extrapolating results at elevated temperatures to room temperature. The chemiluminescence method, because of its extreme sensitivity, permitted measurements down to room temperature. Temperature dependence results for the chemiluminescence experiments were in agreement with accelerated aging experiments in the 70-100°C range done with the same papers at the Library of Congress. These results thus give support to conclusions drawn from accelerated aging experiments.

In addition to looking at effects of temperature, samples of paper were cycled between moist and dry atmospheres. This produced a striking increase in light emission when the humidity was changed. This suggests, as has long been supposed, that fluctuating humidity is detrimental to paper.

Effects of Reducing Agents

Partial oxidation of paper makes it more readily hydrolyzed. Researchers at the Library of Congress[7] have studied the use of sodium borohydride to reduce the oxidized functional groups. It was found that such treatment improved brightness of paper as well as brightness retention, in addition to increasing folding endurance. Sodium borohydride has been found to be an effective addition to alkaline pulping liquors but is too expensive to be used in the quantities required to make it effective.[8]

Changes in Crystallinity

As mentioned earlier, cellulose consists of crystalline regions characterized by regular order and disordered amorphous regions, the latter being responsible for the ability to absorb moisture and for flexibility of the fibers. Some recent research at the Institute for Paper Chemistry[9] suggests that crystallization processes may be an important factor in aging of cellulose fibers.

Heating sample pulp to 170° for two hours, a treatment similar to what pulp experiences in a typical pulping process, showed a deterioration in all papermaking properties. The degree of crystallinity was measured using X-ray diffraction methods. The treated pulp showed a significant increase in crystallinity. Tensile strength decreased by 20 percent, burst by 30 percent and tear strength by 45 percent. Water retention characteristics declined to 60 percent of original values. All of the changes reflect an increase in crystallinity. The small degree of chemical degradation resulting from the treatment was not sufficient to account for the observed change.

Elevated temperatures enhance molecular mobility and accelerate the ordering process. The presence of water was also found to promote the crystallization process.

The degree of polymerization of the cellulose was also found to be important. Ordering increased with decrease in molecular weight or degree of polymerization. Samples with a degree of polymerization (DP) greater than 1000 were unaffected by exposure to water at room temperature while samples with a DP less than 100 crystallized on exposure to the moisture content in the laboratory atmosphere.

These findings have several implications for conservation. Chain scission due to acid hydrolysis causes a reduction in the degree of polymerization giving not only an inherent reduction in the tensile strength of the fibers but also enhanced opportunities for crystallization with resulting embrittlement.

The effect of the ordering process must be considered in the interpretation of accelerated aging results. The temperature dependence of ordering and of the chemical degradation processes may well be quite different. The amount of moisture in these tests will very likely influence the rate of each of the processes differently.

Photochemical Deterioration

Light, particularly light in the ultraviolet region of the spectrum, is damaging to paper. Pure cellulose is very resistant to photochemical attack, but many of the impurities in paper, especially lignin, are sensitive to light. Lignin in groundwood paper, such as newsprint, yellows very rapidly on exposure to sunlight primarily due to photochemical oxidation. Rosin size, the presence of metal ions, and chemical bleaching all contribute to increased photochemical attack on paper. A variety of reactions are caused by the absorption of light, including oxidation. Depending on the paper and other conditions, paper may yellow and darken or bleach when irradiated. Some of the products of photochemical attack (primarily peroxides) are themselves thermally and photochemically unstable, causing further degradation.

It has been found that the introduction of small amounts of iodide in the form of hydrogen iodide gas may afford protection against oxidation.[10] This has prompted researchers at the Library of Congress to consider the possibility of introducing antioxidants into paper by gas phase techniques.

Crosslinking

Hydrolysis, oxidation and reactions of the products of these processes, plus reactions of a variety of functional groups in cellulose and other ingredients in paper cause crosslinking (the bonding of separate cellulose molecules at various points on the chains). A degree of crosslinking improves paper strength, but too much results in embrittlement.

Current Developments in the Paper Industry

The major development today in the paper industry is a trend to alkaline paper. The Library of Congress has been monitoring the pH of books coming into its collection and finds that about 25 percent of the American books and about 50 percent of the European books are made of alkaline paper. Five years ago less than 1 percent of the books tested were made with alkaline paper.[11]

Alkaline paper is paper made in a neutral or slightly alkaline system and contains calcium carbonate as a filler. The calcium carbonate acts as a buffer, neutralizing any acid which may develop in the paper over time. Alum-rosin size is not compatible with alkaline papermaking. Since the 1950s with the introduction by Hercules Corporation of a synthetic alkaline sizing material, Aquapel, it has been possible to size alkaline papers in the machine. There are now several alkaline sizes available.

The Europeans have been leading in the move to alkaline paper, because calcium carbonate is less expensive in Europe and because energy and fiber costs are significantly higher. The alkaline process provides cost savings in these areas. Several American companies are currently producing alkaline paper and the number is growing as the industry learns to operate with the new processes and as its many advantages are recognized.

The reasons for this trend are economic. Paper consumption is conservatively expected to double in the next twenty-five years. During this period fiber and energy are expected to double in real cost and the cost of water is expected to triple.[12]

Alkaline papermaking offers a potential savings in all of these areas plus a number of other advantages.[13]

—A stronger paper is produced permitting savings through weight reduction, increased filler content, the use of weaker, less-expensive fibers or the elimination of dry strength resins.

—Waste water and byproducts can be recycled, reducing pollution control cost and conserving resources.
—Calcium carbonate is already widely used as a pigment in paper coating. The alkaline process allows easy recycling of such papers.
—The machinery lasts longer. The acid process is corrosive, and recycling waste water in this process increases the corrosion problem and causes scaling problems. An alkaline papermaking environment is noncorrosive, extending machine life and reducing maintenance costs. With a single paper machine costing upward of $50 million, this can be significant.
—A higher brightness is achieved. Calcium carbonate, in addition to its acting as a buffer, is a pigment with high brightness.
—Calcium carbonate is cheaper than the titanium dioxide it replaces.
—The waste water is at about pH7 so neutralization of effluent discharge is not required.
—Energy may be conserved in three areas—drying, refining, and in some cases process waste water temperature control. Alkaline paper has been found to drain faster, thereby reducing drying costs. The improved strength of the paper can permit a reduction in refining with a subsequent energy savings.

Some mills maintain high stock temperatures. One mill, on changing from acid to alkaline papermaking was able to reduce its effluent discharge from 14,000 gal./ton to 5,000 gal./ton. The energy savings in not having to heat 9,000 gal./ton to 150°C amounted to more than $10/ton.[14]
—Alkaline paper recycles better, giving a stronger recycled product.[15]
—No capital expenditure is required to convert. The same machinery is used in both acid and neutral or alkaline papermaking.
—Productivity is increased as a result of reduced down time of machinery due to maintenance problems or periodic cleaning. The alkaline process is cleaner.
—The product resists aging.

Not all of the above advantages are likely to be realized in any individual mill. The particular benefits gained will vary, depending on local conditions, the grades of paper being produced, and other factors. An example cited in the literature[16] showed a savings of $42/ton in primary raw materials and a savings in reduced water consumption of $15/ton, giving a $57/ton savings (10 percent of the cost of the finished product).

The lasting quality of the paper carries little or no weight with the producers. They are in general convinced that permanence will not sell paper.

Barrow, working with chemical and paper companies, showed many years ago that permanent/durable paper could be produced commercially from wood pulp. Alkaline sizes have been available for more than twenty years. Librarians, archivists, and publishers must take some of the blame for not forcing the industry to provide permanent/durable alkaline paper and for not using it when it was available. To put things in perspective, however, it should be remembered that only about 15 percent of the total paper production is for printing purposes,[17] and only a little more than 1 percent is book publishing paper.[18] Fortunately, the economics of the process are sufficient to prompt many of the producers to switch to alkaline paper production and the problem of rapid decay of paper may be solved by default in the course of the next twenty-five years or so.

There are some problems to be overcome in making the transition to alkaline paper. The conversion itself is expensive, requiring retraining of workers, cleaning of equipment, and a completely new set of additives (dyestuffs, starches, defoamers, retention aids) need to be introduced. Paper which contains lignin (groundwood paper) has problems—the pulp is sticky and brownish in color and the resulting paper is reduced in brightness. By making the proper adjustments however, groundwood paper can be made with neutral or alkaline size and calcium carbonate filler. This is being done increasingly in Europe. The sticking problem (press sticking) is present, though to a lesser extent, even using pulp free of lignin. Release agents are added to counteract this. The feel of the paper may be different.

Though alkaline paper seems to be well established, there is still research to be done to improve the process, and since most companies are fairly new to the process there is promise for measurable improvement as they learn more about it. Overall the advantages outweigh the problems and those producers who have switched say they would not change back.

Converting to alkaline paper is sufficiently costly and disruptive that it requires a total commitment at all levels from the top management down to assure success. It is a complex and expensive transition, but one that pays dividends in the long run.

One economic pressure working against high-quality alkaline paper is the cost of wood and the desire to get maximum yield from the wood used. Groundwood gives about a 90-95 percent yield, compared to a 40-50 percent yield for good-quality paper. Thus there are economic pressures to use groundwood paper. A newer method, Thermo-Mechanical Pulping, is growing rapidly.[19] It requires more power, but its yield is as high as regular stone groundwood and the paper is strong enough to be used alone. (Groundwood pulp is generally blended with higher quality chemical pulp for added strength.) Thermo-Mechanical Pulp, like groundwood, contains the lignin and other materials from the wood which contribute to its poor lasting qualities. For certain types of publications the situation will probably get worse even though alkaline paper is becoming more available. This is seen in Europe where many magazines, brochures, and ephemera are being printed on groundwood paper. Groundwood paper is being used increasingly in textbooks and some reference books. These papers are almost always coated, which significantly increases their longevity although they cannot be called archival. A groundwood paper which uncoated might last twenty-five years will, if coated, still be handleable after fifty and perhaps up to seventy-five or one hundred years.[20]

Another trend in papermaking is the increasing use of hardwoods.[21] Hardwoods are more plentiful and are cheaper than softwood. Paper from hardwoods generally gives better printing quality, but is weaker.

Oxidation

The problem of paper oxidation has received less attention, and less effort is being expended in the industry to deal with it. As with acidity, the concern in the industry is not with paper longevity but with other factors such as brightness and reduced yellowing. Some efforts are being made to reduce metal ion levels in paper. As noted above, these catalyze paper oxidation and the oxidation of sulfur dioxide to sulfur trioxide.

Bleaching

Bleaching of pulp is another area of change and exploration.[22] The effluents from bleaching plants are a major problem. Environmental pollution controls together with other changes in paper technology are causing paper companies to look for better methods of bleaching. Historically, chlorine, calcium hypochlorite, and chlorine dioxide have been popular bleaching agents. Oxygen bleaching was introduced on a commercial scale in 1970. Oxygen bleaching allows for simpler pollution control methods, but the bleaching is not as effective.

Some experimentation with ozone as a bleaching agent has been done. New bleaches and new methods will very likely be introduced in the future. The implication for permanence and durability are not clear at this point. Whatever changes are made will no doubt be made for reasons other than the effects on paper longevity.

Standards for Permanent/Durable Paper

Though librarians and archivists can claim little credit for the move to alkaline papermaking they should be able to exert influence in the use of this paper for the books and other paper materials that they collect.

Requirements for permanence and durability should be included in specifications for items being purchased. There are established standards which can be referenced in purchase orders, and to which paper manufacturers can look to for guidance. To be informed customers, purchasers should be familiar with the appropriate standards.

American Society for Testing and Materials (ASTM) standards of interest are:[23]

D3290 Bond and Ledger Papers for Permanent Records
D3458-75 Copies from Office Copying Machines for Permanent Records
D3301-74 File Folders for Storage of Permanent Records
D3208-76 Manifold Papers for Permanent Records

The National Historical Publications and Records Commission provides standards for paper, printing and binding.[24] Barrow Research Laboratory published specifications for permanent/durable paper.[25]

Current activities in this area include the work of the Committee on Production Guidelines for Book Longevity which operates as part of the Council on Library Resources. This group, made up of representatives from publishing, paper manufacturing, and library preservation programs, has recently issued an "Interim Report on Book Paper."[26] The report offers guidelines on paper which are adapted and simplified from the standards set by the National Historical Publications and Records Commission, the Library of Congress, and the ASTM/ANSI Standard Specification for Bond and Ledger Papers for Permanent Records. The report also addresses the question of what types of publications should be printed on such paper and what categories might be considered lower priority with respect to permanence. Some commercial sources of acid-free paper are listed.

Other collective efforts toward creating a conservation-conscious and informed consumer include the activities of the Association of Research Libraries, Preservation Committee and Office of Management Studies; the Preservation of Library Materials Section of the American Library Association's Resources and Technical Services Division; the Study Committee on Libraries and Archives of the National Conservation Advisory Council; the Society of American Archivists; and the American Association for State and Local History.

Conclusion

While we still have much to learn, and there is room for further progress, it is not only possible, but it is in the papermaker's own economic interests to produce permanent/durable paper. Such paper can reasonably be expected to last several hundred years instead of the twenty-five to fifty years for modern acidic book paper. There is thus no excuse for producing books and other publications of lasting importance on anything other than paper meeting existing standards for permanence and durability. There is reason to hope that this will finally happen. It is up to every librarian, publisher and paper consumer to insist that it does and to use whatever influence we have to speed this process.

NOTES

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DISCUSSION

Philip A. Metzger (School of Medicine, Southern Illinois University at Carbondale): I was interested in your figure of 25 to 50 percent of the new books being on alkaline paper. With the introduction of mass deacidification does that mean that essentially 25 to 50 percent of the books that might be mass-deacidified might not really need it?

Gerald Lundeen: The books that are being considered for mass deacidification are books that have been in the collection for some time. The only ones that are found to be on alkaline paper are the ones that have been coming into the collection within the last five years, but mostly within the last one or two years.

Metzger: But aren't those really the prime candidates for mass deacidification before they degrade?

Lundeen: It has been suggested that books that are printed on alkaline paper ought to be so identified. The publisher ought to make a statement in the book saying, "This book is made from paper meeting such and such standards." That way we won't unnecessarily treat these books, as you point out. Along with that question, identifying books for deacidification or treatment that are not so identified by a statement from the publisher requires testing the paper with pH detectors. The problem of identifying books that may require treatment because of acidity (if the books are not identified by the publisher as being printed on permanent durable paper) forces us to use a chemical test of some sort to see whether it's acidic or basic. You can have acidic paper that is coated with calcium carbonate, and, if you use the wrong sorts of tests, it will test basic even though the core of the paper is acidic. And so that's something you've got to be careful about. That's one of the reasons for recommending that publishers provide this information in books that they have printed on permanent paper.

D.W. Krummel (Graduate School of Library and Information Science, University of Illinois at Urbana-Champaign): I think one of your statements does need qualification. The library profession—Verner Clapp in particular—has been calling for an improvement of that situation. Library publications directed toward permanent library collections (e.g., the imprints of G.K. Hall and Scarecrow, in particular) conspicuously mention the quality of the paper. We've had less success in working with the publishers who are not directed primarily toward library markets. But since the late 1950s I think we have had a significant impact. I think that should be made a part of the record, but I'm not sure what impact, if any, we've had on the new machinery which has been developed that dramatically changed the character of paper.

Lundeen: That's a good point. I didn't mean to slight that, and when I said we couldn't claim much credit for the transition to alkaline paper, it's not from lack of trying. As Don [Krummel] suggested, we've been calling for a transition for a long time but economics are what, for the most part, carry the weight with the papermakers. There are some exceptions in terms of papermakers, too. S.D. Warren has been making alkaline paper for many years (since the late 1950s). Recognizing that permanence is important, few other paper companies have been doing this as well but the majority of the papermakers are convinced only by dollars.

Charles Davis (Graduate School of Library and Information Science, University of Illinois at Urbana-Champaign): I was wondering about the effects of low temperature. Has anybody extrapolated with enough confidence to assert that we should move our archives to Greenland?

Lundeen: I'm not sure if I'm remembering my numbers right but I think the suggestion has been made that if we reduce the temperature by 25 degrees Celsius below room temperature, paper that normally would last on the order of 50 years or so is extended to 4000 years. And by going another 25 degrees lower, you get another 40,000 years or thereabouts. Some measurements were done on paper from the expedition of Scott, who froze to death at the South Pole. His materials were left there. Notebooks from that expedition were retrieved sometime in the late 1950s and this paper has been examined and compared to essentially the same kind of paper to see what the effect was of this prolonged storage in Antarctica. The effects are not nearly as dramatic as was expected based on those projections. There was a stabilizing effect due to the low temperatures but it wasn't nearly as much as we would have expected based on the extrapolations that people have been making.

Larry Hall (Alma College, Alma, Michigan): You made a few references to variations of humidity and their effect on paper longevity. Could you speak to that further?

Lundeen: This is a question which is still up in the air. The accelerated aging tests have been done in essentially two different modes, one with dry air with essentially zero humidity. People have criticized that as being unrealistic because you don't store books in dry air. The other series of tests have been done in 50 percent humidity and these, likewise, have been criticized because that's perhaps a bit high although maybe not that far off, depending on where you live. In Hawaii that's a little bit low. Measurements comparing the accelerated aging tests with long-term tests seem to indicate that really some place in between is probably the best condition, but where in between hasn't been decided yet—maybe 10 to 20 percent humidity for the accelerated aging tests. There are some fairly well accepted guidelines for storage under normal temperatures and relative humidities, and there, around 50 percent or so is accepted. A more crucial problem may be fluctuations in humidity which cause paper to be stressed by absorption and desorption of moisture.