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The Testing of Laminates and Synthetic Papers as Currency Substrates

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National Bureau of Standards
Center for Materials Science
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Final Report for the Period
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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Executive Summary

This report is divided into three parts. Part A is concerned with the preparation and testing of laminates. Part B deals with the testing of synthetic polymeric papers obtained from the Bureau of Engraving and Printing (BEP), while Part C includes discussion of the test results, comparisons of property data, and recommendations associated with the laminates and synthetic papers.

The laminates were prepared from a special currency paper having reduced thickness (CPRT) in order to compensate for the thicknesses of the outer plastic films. Compression molding and roll lamination techniques, employing bench-scale sized equipment, were used to prepare these laminates from a variety of thin, transparent, plastic films. The complete physical and mechanical test determinations are reported for CPRT and three laminates prepared from low density polyethylene (LDPE), polycaproamide (N-6), and biaxially oriented polypropylene (BPP). None of the three laminates tested have better properties in "all" categories of concern than "does" the currency paper now in use. Overall, the CPRT-BPP laminate exhibited more favorable properties in more categories than did either N-6 or LDPE laminates. Unfortunately, the low density elongation to break values inherent in the CPRT, especially in the machine direction (MD), are also apparent in the laminates in the MD. For this reason, due

to the poor performance values for CPRT, emphasis for this project shifted from testing CPRT-based laminates to the testing of polymeric synthetic papers as possible currency substrates.

Three synthetic papers and two polymeric film (sheet) materials were obtained from BEP for property determinations. The synthetic papers were: Tyvek-1058 (high density polyethylene); Nomex-410 and -414 (polyarylamide), and Texoprint (synthetic fibers and latexes). Two types of Melinex film -377 and -442 (polyethylene terephthalate) were also provided for testing for reasons internal to BEP. Of the synthetic papers tested, Nomex-410 has better overall properties, both physically and mechanically, than any of the materials processed. The main detriments of Nomex-410 are its rough hand or feel, and the fact that Nomex-410 will absorb approximately 1% water for each 10% rise in relative humidity. Tyvek-1058 does have higher values for Elmendorf tear resistance, MIT fold endurance, and elongation to break, but it suffers from low cantilever stiffness (flexed) and low initial modulus. Texoprint paper also has high cantilever stiffness values, but when flexed, considerable loss of stiffness occurs in the direction of flex. Texoprint paper does not meet the minimum requirements for fold endurance in either the machine or cross direction.

The single-ply synthetic paper sheet would have advantages not inherent in a three-ply laminate. The problems of delamination and edge-sealing would be avoided. Although most of the synthetic papers are polymeric in structure, the texture of the synthetic surfaces is more akin to conventional paper than to plastic films, so that blocking tendencies, associated with glossy film surfaces, would appear to be minimal. Still, abrasion, soil, ultraviolet light resistance, printability, and esthetic qualities of the synthetic paper selected as a currency paper substitute would have to be evaluated.

INTRODUCTION

The cost of maintaining an adequate supply of currency could be significantly reduced by increasing the circulation lifetime. The principal factor controlling lifetime is the deterioration of the mechanical properties, particularly flexure, of the currency substrate. It is well-known that synthetic polymers, either as coatings or laminates, can improve the flexure properties of paper. Also an entirely synthetic polymer substrate would be expected to result in a more durable currency. In addition to the choice of coatings or laminates there are a large number of synthetic polymers that may be suitable materials. Thus, the task of identifying a suitable system for currency is formidable without further selection criteria. We present here the final report of our joint effort with the Bureau of Engraving and Printing to develop such selection criteria.

Objectives for this Project

1. To locate and obtain polymeric films and adhesives suitable for lamination with currency paper.
2. To study the conditions necessary to produce acceptable laminates by compression molding techniques and/or roll lamination procedures.
3. To screen potential film-currency paper laminates for cantilever stiffness, Elmendorf tear resistance, and flex-life or delamination properties. These tests determine whether or not candidate laminates are processed further through the complete mechanical test program.

4. Determine the changes in property values of the laminates or similar polymeric papers after flexing in both the machine and cross directions. The change, if any, in property values of the flexed laminate determines the usefulness of the laminate as a substitute currency substrate
5. Develop property selection criteria for successful currency paper laminates or single sheet polymeric papers.

Part A: Laminates

I. Procurement of Plastic Films, Adhesives, and Currency Papers

For this project the assumption was made that the end product plastic laminate of currency paper would have the same physical dimensions as currency paper now in circulation, nominally, 15.56 cm L x 6.51 cm W x 0.0114 cm T. Of these dimensions, the gauge thickness of the plastic film was our main priority item. On this basis, a considerable effort was expended to locate and accumulate a wide variety of thin, colorless, and transparent plastic films. Our primary interests were in films in the thickness range from 12.7 μm to 25.4 μm. The actual film thickness preferred was determined by the thickness (92 μm) of the currency paper employed in the project. Films, with thicknesses up to 38.1 μm, were also acquired to prepare test laminates from polymers where thin films were not available for a specific type of plastic.

A good cross-section of coated and uncoated films of different polymeric structures was obtained from various sources (Table 1). Some quantities of film were not as plentiful as others, but sufficient amounts of each type were available to produce relevant test specimens. Most of the coated films employed polyvinylidene dichloride (PVDC) as a barrier film. PVDC was used also as an adhesive to bond the film to currency paper in some cases. In the event of easy film delamination during testing, we acquired, at the same time as the films, some common as well as specific adhesives (Table 2) which can be applied to the uncoated counterpart films. In general, one type of adhesive can be used for several candidate substrates, i.e., polar adhesives for polar substrates and non polar adhesives for non polar substrates with variations therein.

Table 1 lists the films on hand, the supplier, gauge thickness in micrometers (μm), and the coating if applicable. The films presented in Table 1 are of the type more generally used in the packaging industry and are more readily available in large quantities. Some specific films such as the fluorocarbons, are also listed because of some specific property inherent in the polymer film. Most of the films given in Table 1 will also accept printing with inks properly formulated for the type of polymer involved in the laminate.

On July 7, 1982, 40 sheets (65 cm L x 65 cm W x 0.014 cm T) of non-distinctive currency paper (NDCP) and on September 1, 1982, 100 sheets of currency paper (63 cm L x 56 cm W x 0.0092 cm T) having reduced thickness (CPRT) for laminations with plastic films were received from Mr. John Mercer at the Bureau of Engraving and Printing (BEP). Suitable security arrangements were made to store the papers when not in a work situation. The unused currency papers and scraps were set aside for return to BEP upon completion of the project.

Several types of synthetic papers and plastic films were also obtained from the Bureau of Engraving and Printing (BEP) for physical and mechanical property determinations.

Some of the more important physical and mechanical properties and other useful data for the plastic films on hand (Table 1) were gleaned from many sources(1,2) in addition to the technical literature provided by the manufacturer of the films. This information served as a guide to select or eliminate certain types of films whose properties did or did not conform to those required for currency paper laminates. Initially, primary considerations were given to those films whose moduli, tensile properties, tear and fold endurances, and elongations were in a range of values at least equal to or better than those values associated for unprinted currency paper(3,4).

II. Paper Cutting and Accountability

The currency paper having reduced thickness (CPRT) obtained from BEP was used exclusively to prepare laminates with plastic films of appropriate thicknesses for physical and mechanical property determinations.

Statistical considerations led to the decision to prepare thirty (30) laminates in each series, i.e., machine (MD) and cross (CD) directions, to be used in this project. The thirty laminates were cut and divided as done previously for other currency papers(5,6).

a. Ten (10) laminates from CPRT cut in the machine direction (MD), which is along the short side (56 cm) of the sheet. Each sheet produces 8 (15 x 28 cm^2) pieces.

b. Ten samples prepared from CPRT cut in the cross or transverse direction (CD), which is along the long side (63 cm) of the sheet. Each sheet produces 6 (15 x 30 cm^2) pieces with 1 (10 x 63 cm^2) piece remaining.

c. Ten samples to be used as controls and prepared from the above pieces in either machine or cross directions, but will not be pre-flexed before testing.

To date, thirty seven sheets of CPRT have been cut into machine direction or cross direction pieces for laminate preparations. One piece from each cut sheet has been set aside for control testing of properties of CPRT without lamination to provide some minimum data requirements.

To help account for the currency paper on hand and used, each sheet was assigned a number (1 to 100). As each sheet was cut, the individual pieces were numbered sequentially, along with its directional cut, i.e., $\overrightarrow{1\text{-}1}$, $\overrightarrow{1\text{-}2}$, $\overrightarrow{1\text{-}3}$, etc. Further cuts of each individual piece would follow the same pattern, i.e., piece $\overrightarrow{1\text{-}1}$, further cut into two pieces would give $\overrightarrow{1\text{-}1\text{-}1}$ and $\overrightarrow{1\text{-}1\text{-}2}$. By this method, it was anticipated that a complete record can be maintained for each sheet of CPRT. As it will be shown later, for complete testing, each laminate was cut further into eight additional pieces of varying dimensions for specific testing applications (Cf, Fig. 1)(5).

III. Lamination Methods

There are two general laboratory methods available for the preparation of test laminates on a small scale, i.e., a) compression molding and b) roll lamination.

a. Compression Molding Techniques

1. Apparatus

In compression molding, the materials for the laminate (film, adhesive and paper), sometimes called "the sandwich", were assembled outside the press between two highly polished chrome-steel plates. When completed, the entire assembly was placed between the heated platens of the press. Some pre-heat time was allowed to bring the outer cover plates and the inner laminate materials to the working temperature used for a particular lamination. Pressure was then applied for a given time period, released and the laminate assembly was removed from the press and allowed to cool inside the cover plates.

For the large size (15 x 30 cm^2) laminations, a press of 50-ton capacity was employed which contained 38 cm^2 steam-heated/water-cooled platens with a semi-automatic positioning mode to raise or lower the platens. The larger press facilitates ease of operation and assures that all laminates in the same series have received similar thermal and pressure treatments.

Initially, a small manual press, having 23 cm^2 platens, was used to prepare small laminates (13 x 13 cm^2) from 100% cotton paper and various plastic films as well as from non-distinctive currency paper (NDCP) to test laminating conditions and procedures.

1. Sample Layup for Compression Molding

During the initial layup of the laminate materials over the metal plate some difficulty was encountered with the thin films staying flat due to the static electricity acquired on the film surfaces. These charges had to be neutralized with an air ionization device several times during the assembly process. Even when electrically neutral, these thin films (12.7 to 19.1 μm) are difficult to handle by hand without forming creases or wrinkles in their surfaces during the layup process. The problem of creasing can be partially avoided by placing a backing-film or release paper between the metal plates and the outer surfaces of the laminate films. This allows for some movement of the film in all directions without stretching or distorting the final laminate surfaces.

The dimensions of the metal laminating plates were: 35 cm L x 20 cm W x 0.32 cm T. These oversized plates are 5 cm longer and wider than the standard laminate size (30 x 15 cm^2) needed for this project. With these plates, the laminate materials are completely enclosed between the plates during compression and assures that some pressure has been equally applied to the edges of the laminates. With plates equal in size to the laminate materials, the edges were at or near atmospheric pressure and complete edge-sealing of the laminate was never accomplished. In the latter case, delamination of outer plastic film always occurred when manually flexed in MD and CD.

The type of plastic films and conditions employed to prepare the standard size (15 x 30 cm^2) laminates are given in Tables 3 and 4.

b. Roll Laminations

1. Apparatus

A laboratory bench top coater-laminator apparatus was used for roll laminations of coated or uncoated films and currency paper having reduced thickness (CPRT). The apparatus essentially contains two 10.2 cm diameter x 38.1 cm wide rollers. The upper roller is covered with neoprene (65 shore A durometer hardness) and the lower roller is constructed of smooth, highly polished chrome steel which can be heated when necessary. Two 5.1 cm air cylinders with pressure regulators, a four way valve and pressure gauge provide the nip pressure adjustments. The nip opening can be controlled by micrometric adjustments of set screws located at each end of the roller. For coating, the apparatus contains a dip pan which rests upon a hot plate built into an elevator for raising or lowering the pan beneath the lower steel roller. For simultaneous two side laminations, a second, heated, smooth steel roller replaces the upper neoprene roller in order to provide equivalent thermal treatment on both sides of the laminate during processing. Due to delivery time differentials between the arrival of the coater-laminator and the second chrome-steel roller late in the project, only single side roll laminations were performed during this project.

2. Sample Layup for Roll Lamination

In single-side laminations, one side of the CPRT is first coated with adhesive; dried to tack; then covered with the desired film, and roll laminated under specific conditions peculiar to the adhesive and film. The reverse side is then treated in a similar fashion while protecting the already laminated first side with silicone release paper. There are some difficulties encountered while using the extant equipment under these conditions. Most noticeably, reheating of the laminated first side causes the adhesive to soften which results in additional movement of the laminated film which leads to the formation of occasional streaks in the surface. Ideally, with tension unwind accessories, the films and the coated CPRT would enter the rollers at the same time eliminating the extra precaution necessary to remove trapped air between the adhesive and film during preparation of the "sandwich" prior to lamination. Trapped air, if not removed or squeezed out during the process will lead to unnecessary blistering of the laminate. Delamination of the films will occur more readily from a blister-containing laminate during flexing.

For these small-sized laminates (15 x 30 cm^2), the use of thin plastic films as the outer covers requires some support backing material to hold the "sandwich" laminate in place as it enters the rollers. Silicone release paper (127 µm) and the paper blotters (584 µm) used to protect the chrome plates in compression molding serve this purpose very well. The temperature, nip opening and roll speed must be adjusted to compensate for the differences in thickness of these support materials. Generally the nip opening between the rollers is set at one-half of the total thickness of the material entering the rollers. Usually, the temperature is increased, and the roll speed decreased for thick samples, to allow for adequate heat transfer to proceed from the heated rolls through to the laminate during processing. The conditions employed to prepare some test laminates by roll laminations from CPRT and various plastic films are listed in Table 5.

IV. Procedure for Adhesive Application

For the preparations of laminates from uncoated, thin (25.4 μm) plastic films and currency paper, it was found to be easier to manually apply the adhesive coating to the CPRT rather than to the thin films by the brush technique. A steel straight-edge was employed to remove excess adhesive. This method, of coating the paper rather than the plastic film eliminates probable solvent damage to the film surfaces due to long residence times of the solvent during the drying period. No such surface damage was anticipated by pre-coating the paper.

In general, the CPRT sheet is clamped to a release paper on a glass support and the coating applied by a brush. The residence time allowed is 15 seconds for solvent based adhesives, and 30 seconds for aqueous based systems. The excess coating is then removed by the straight edge. When dry, the paper is turned to the reverse side and the process is repeated. Each side of the paper is individually coated. In this method, the amount of coating deposited per unit area depends principally upon the concentrations of solids in the adhesive system employed. Concentrations of material deposited upon the surface can be varied by appropriate dilution technique before application. Water based adhesive systems cause the thin currency paper (CPRT) to pucker which results in high and low spots when the excess adhesive is removed by a straight edge. Often, when wet, the paper snags and tears easily during removal of the excess adhesive. No problems of this type were encountered with solvent based adhesives. For currency paper coated by this process, the coated surfaces varied as much as 7.6 μm (0.3 mil) per side, but many of the high and low spots became more even during the molding process as evidenced by the decrease in non-uniformity in thickness of the finished laminates.

The coater-laminator apparatus arrived too late near the end of the project for machine coating of currency paper or films to be a viable alternative to the above brush method.

The conditions used to prepare test laminates from the coated paper and various films are given in Tables 4 and 5, along with some visual observations and flex behavior.

V. Preparation of Laminates

a. General Conditions for Laminations

Most of the laminates containing thin plastic films and currency paper having reduced thickness (CPRT) were prepared by compression molding, especially those laminates used for the specific test program (Table 3). Other laminates used in the screening program were prepared by both compression molding (Table 4) and roll lamination (Table 5).

The heat seal temperature range used to prepare laminates from coated films are those recommended by the manufacturers of the films. For adhesive coated paper and uncoated films, the data provided by the adhesive manufacturers were employed.

The two pressure ranges were: 1) contact pressures, i.e., 0-0.52 MPa and 2) low pressures, 0.52-3.4 MPa. Pressures above 3.4 MPa would probably distort most of these thin films needed for this project, and as a result, high pressure laminations were not included in this study.

b. Laminates From Non-Distinctive Currency Paper (NDCP)

Non-distinctive currency paper (NDCP) was employed as an interim substrate for laminations with plastic films until the arrival of the thin currency paper for use in this project. Since the thickness of the paper is 140 µm (5.5 mils), laminates prepared from this paper are generally too thick. Therefore, no mechanical property determinations were planned for these laminates. Instead, since NDCP is assumed to have the same chemical composition as the currency paper to be used in this project, NDCP was employed to determine laminating conditions and to provide visual property assessments as to seals, blistering, feel and manual flex/delamination from a variety of plastic films. In general, the laminates prepared from NDCP are similar to those prepared from the thin currency paper (CPRT) as reported in Table 3. Therefore, no further work was done with NDCP.

c. Laminates From Currency Paper Having Reduced Thickness (CPRT)

The sizes of all laminates prepared from the new, thinner currency paper (CPRT) are 15 x 28 cm^2 in the MD and 15 x 30 cm^2 in the CD according to the method of cutting the paper(5,6). The laminates discussed in this section are listed in Table 3. These laminates were used for physical and mechanical property determinations.

1. From Biax-Polypropylene (BPP)

The polypropylene film used for these laminations with CPRT is biaxially (balanced) oriented (Table 1, #17) and is coated with polyvinylidene chloride (PVDC). The film thickness is 17.8 µm. The conditions used for the preparations of these laminates are listed in Table 3 (#1). Thirty laminates were prepared for physical and mechanical property determinations. Due to the biaxial orientation of the film, shrinkage of the film will occur above 100 °C in both the machine (MD) and the cross (CD) directions. Slightly more shrinkage occurs in the MD (-5.5%) than in the CD (-4.5%). Because of the shrinkage, it is necessary to provide a release (backing) film between the chrome plates and the laminate to insure smooth laminate production. Without this release film, (in this case, PET, 25.4 µm thick), the BPP films adhere slightly to the metal plates, and shrinkage occurs in an uneven fashion leading to a severely blistered laminate. The laminates, prepared from BPP and currency paper having reduced thickness (CPRT) as given in Table 3 (#1), employed the release film procedure. The seals, flex and visual appearances of this high gloss laminate were very good. But, as it will be discussed in a later section, there was little or no improvement in the propagating tear resistance for this laminate even though other physical and mechanical properties were enhanced.

2. Polycaproamide (N-6)

The polycaproamide film used for laminations with the thin currency paper is Nylon-6 (Table 1, #13). It is used extensively as a packaging material. The film thickness is 15.2 µm and it is also coated with PVDC which is used as a barrier film. Like most polyamides, Nylon-6 is hydrophilic and will absorb moisture. The moisture content varies with the relative humidity and at 50% relative humidity and 23 °C, Nylon-6 contains from 1.5 to 2.0% moisture. At increased levels, moisture acts a a plasticizer for Nylon-6 which causes some loss of stiffness in the film. This behavior is reversible.

In Table 3, the conditions are given for the preparation of laminates from N-6 and CPRT as well as some visual observations of the end product laminate. Again, the hand and feel of these laminates were good and no flex-delamination was observed.

In addition to the sample laminates prepared above for testing, twenty two laminates were prepared from CPRT and biax-polypropylene (BPP) (Table 3, #2) and polycaproamide (N-6) (Table 3, #4) which were sent to BEP for further observational and investigational purposes.

3. Low Density Polyethylene (LDPE)

The low density polyethylene film (Table 1, #8) used for laminate preparation with CPRT is the type used as plastic wrapping and it can be found in most grocery stores. The thickness of the film is 12.7 µm and at this thickness, the film lacks sufficient stiffness to be a good laminate material. However, by the use of high temperatures and pressures, the film was effectively used to impregnate a coating of low density polyethylene upon the CPRT. For this coated preparation, a release film of PET was necessary between the chrome plates and the plastic-covered paper. The LDPE coated paper easily de-laminates from PET when cooled. With no change in thickness between the original CPRT and the LDPE coated CPRT, the main potential of this preparation is to bind other plastic films, such as polypropylene, with CPRT into a laminate of proper thickness. The conditions employed to prepare the LDPE coated CPRT are listed in Table 3, (#5) along with some visual observations of the end product.

d. Preparation of Test Laminates From CPRT and Various Plastic Films

The test samples described in this section were prepared by both compression molding (Table 4) and roll lamination (Table 5). In most cases, uncoated films and CPRT, coated with various adhesive formulations, were the laminate materials. These laminates were prepared in order to test the effectiveness of the adhesives to seal the films to the CPRT, and to determine the effects of the various combinations on the physical properties of the laminate. The final thickness of the plastic covered laminate also bears a direct relationship to the physical and mechanical properties of the sample. Initially, the films were selected on the basis of high tear resistance. These films included the fluorocarbon copolymers, E-CTFE (Table 1, #23), and E-TFE (Table 1, #22). However, for these fluorocarbon films, the inside surfaces of the films must be pretreated or activated, usually by in-line corona discharge treatment, before low temperature bonding can be achieved. The pretreated surfaces deteriorate with time while exposed to moisture. For these films, a special contact adhesive (Table 2, #6) was applied to the CPRT. When dry the adhesive forms a slightly amber colored, flexible film which still contains a small amount of tack. Due to the cohesive strength of this adhesive, the initial alignment of the films during the layup procedure with the coated CPRT must be done very carefully to exclude air as the film is applied to the currency paper. Repositioning of the films after contact has been made is virtually impossible without developing creases and wrinkles in the laminate surfaces. These defects cannot be removed during processing by compression molding or roll lamination and lead to film delaminations from the CPRT. For the fluorocarbon copolymer films, the laminates produced by roll laminations (Table 5, #2, 3, 4 and 5), have good stability and better overall appearances than those prepared by compression molding (Table 4, #6, 7). All have good seals and feel, contain no blisters, and the films did not delaminate on manual flexing.

Several samples of laminates were prepared from E-CTFE and CPRT (Table 4, #6, 7) by compression molding using the same contact adhesive. The laminates appeared to stabilize after preparation but upon standing in the calibration room at 50% relative humidity, all of these samples blistered badly and the films readily delaminated from the paper. This was not the case for the roll laminated samples (Table 5).

In Tables 4 and 5, a number of laminates are listed that were prepared from various films and adhesive formulations in order to provide data concerned with cantilever stiffness (CS) and Elmendorf tear resistance (propagating) of the laminate. Some films when laminated with CPRT have good mechanical properties, but lack the proper stiffness or tear resistance. The type of adhesive employed in the laminate preparation may affect the tear resistance by absorbing the energy in the tear front and dispersing it to the surrounding regions. In this way, it may be possible to convert cost effective films with otherwise excellent properties but which have low tear resistance and stiffness values into acceptable laminate materials.

Some of the films, especially BPP and N-6, have already been used as laminate material and their property values are known (Cf, Tables 7, 8, 9, 10). For these films, the effect of employing a different adhesive upon tear resistance and stiffness can be readily discernible providing that the nominal thicknesses of the laminates are maintained.

The laminates prepared as test samples from various plastic films and adhesives are listed in Tables 4 and 5. The conditions used to prepare the laminates as well as their visual appearances are also given in the tables.

The use of the polyethylene coated CPRT as a laminate substrate with biax-polypropylene film (Table 4, #1) resulted in a laminate which upon manual flexing caused the bond between the paper and polyethylene to separate and delaminate. The bond formed between the outer polypropylene and polyethylene is much stronger than that between the paper and polyethylene. Stable laminates from biax-polypropylene (Table 4, #2) or polyvinylidene dichloride (Table 4, #10) were prepared from CPRT when an adhesive especially designed for polypropylene was coated onto the CPRT. The adhesive (Table 3, #12) is a chlorinated, low molecular weight polypropylene and when dry, a flexible, almost colorless film is formed which requires heat activation for bonding with the films. As it will be shown in a later section, there were no improvements in the physical properties of these laminates and as a result, these films were eliminated from the program.

For the polymeric films, such as polycaproamide (Table 4, #3), polyethylene terephthalate (Table 4, #4), polyvinyl chloride (Table 4, #8) and polyvinyl fluoride (Table 4, #9), a general purpose adhesive based upon polyvinyl acetate-polyethylene copolymer (Table 2, #4) was used to coat the CPRT. Two versions of the adhesive were employed for coating the CPRT. The aqueous based emulsion (Table 2, #4) contained 55% solids and usually led to laminates having thicknesses greater than needed. The other solvent-based solution (11% solids in methyl ethyl ketone and prepared in our laboratory) was much easier to apply and yielded laminates close to the desired thicknesses (~114 µm). It should be noted that polyvinyl fluoride film (Table 4, #9), even though the polymer contains a fluorine atom, can be readily sealed to CPRT by the use of this adhesive.

Also in Table 5, several examples are given for Tyvek-1058 (#6, 7, 8) and CPRT (#9, 10) in which a topical coating was applied to the sheets and the coatings were heat sealed by roll pressure between silicone release papers. The coating is predominantly a copolymer of ethylene and vinyl chloride which contain some acrylamide units (Table 2, #5). The amide group allows for further curing or cross-linking to achieve inherent strength. The coating, when dry, is clear and flexible but glossy. Some time is required for the coating to become tack free and under these conditions, initial problems with blocking may become apparent. The coating appears to adhere well to Tyvek-1058 and CPRT and no signs of the coating peeling from the substrates were evident. The results of the screening tests performed on the laminates and coated papers prepared in this grouping will be discussed in a later section.

VI. Physical Properties of Laminates Prepared From Plastic Films and Currency Paper Having Reduced Thickness (CPRT)

The object of this project is to prepare and test plastic film/CPRT laminates for their physical and mechanical properties. The rate of change or deterioration of these properties after the laminate has incurred some form of stress would provide data pertaining to the durability of the laminate. The durability data obtained from these tests could be used then to estimate or predict circulation lifetime of the laminate.

The physical properties(3,4) determined for each series of plastic film-CPRT laminates, before and after flexing, both in the machine and cross directions, were: a) cantilever stiffness (CS), b) Elmendorf tear resistance (EL-TR) c), MIT fold endurance, and d) the average thicknesses of the prepared laminates. A paper flex-testing machine(5) was employed to incur stress upon the laminates. A brief description of each test procedure is given below. A more detailed version of the principles involved in the test modes can be found in the literature cited. Since the laminates, on a weight basis, contained more paper than plastic film and adhesive, the test methods employed the standard procedures as developed by the Technical Association of Pulp and Paper Industries (Tappi)(7) rather than those methods published by the American Society for Testing and Materials (ASTM) for plastic films(8).

a. Physical Test Methods

Prior to testing, all sheet currency paper (CPRT) was pre-conditioned on the dry side for 16 hours before placing the samples in the conditioning atmosphere of 23 °C and 50% relative humidity for an additional 16 hours in accordance with Tappi Method T 402 OS-70(9). After conditioning and flexing, the sheet specimens were cut into pieces having the proper dimensions required for a specific test program as shown in Figure 1(6). These specimens were cut from both the flexed and unflexed (controls) samples in the machine and cross directions.

1. NBS Paper Flex Test

Although the NBS paper flexing machine(5) was specially designed to promote fiber to fiber de-bonding (deterioration) in paper products in a reproducible and uniform manner, the apparatus can also be used to incur stress in a laminate which may result in delamination of the film or changes in other physical and mechanical properties of the laminate. Flexing of the samples is performed in both the machine and cross directions. Generally, the laminates, 15 x 30 cm^2, are flexed 1000 double flexes over 3.18 mm rollers. The laminate is clamped to the machine at one end, while the other is constrained by a 700 g weight. With paper alone, flexing in the machine direction produces more drastic changes in properties than flexing in the cross direction(5). These changes in properties of the paper become evident during subsequent testing for stiffness, tear, fold endurance, and the tensile properties. The effect of the plastic cover on the CPRT was evaluated with respect to changes in these properties.

2. Cantilever Stiffness Test

The Carson and Worthington Stiffness Tester(11) (made at NBS) was employed to determine stiffness of the CPRT and laminates. The length and width of the cantilever bending specimens are adjusted to enable a torque angle reading between 30° and 120° when the sample is bent through an angle of 25°. The test results are given in Tables 7 and 9. Again, as the number increases, the stiffness of the paper or laminates also increases.

3. Elmendorf Tear Test

This test is used to determine the force required to tear a single sheet of paper or in this case, a double ply plastic laminate of paper, after the tear has been initiated. The procedure is set forth in Tappi Method T 414TS-65(9). Essentially it is a measurement of the internal tearing resistance of the paper or laminate. The larger the number, the better tear resistance is shown by the sample. Results from these tests are also shown in Tables 7 and 9.

4. MIT Fold Endurance Test

Three MIT fold testers were used with a 1 kg tension employing the procedures as defined in the Standard Tappi Method T 511SU-69(10). Similar to the curency paper now in use, the minimum number of folds required in either direction is 4000 double folds. In testing sample laminates, no significant decrease in folding endurance should occur for samples flexed

1000 times. For this evaluation, as listed in Tables 7 and 9, only the first three member laminates in each series were run to their break point. For the remaining samples in each series, tests were terminated after 5000 double folds for specimens having a fold endurance greater than 5000 cycles.

5. Thickness

The thicknesses of the sheets of currency paper (CPRT) and its laminates with plastic films were determined by use of a motor-operated dial micrometer graduated from 0 to 100 in increments of 0.0001 inches. The thicknesses of each sheet and laminate were measured at selected points according to Tappi Method T 4110S-76(9) and the thickness was reported as an average value ~~in Tabl~~es 7 and 9.

VII. Discussion of Physical Property Results of CPRT and the Laminates

The results from testing the uncovered CPRT (#2) and those of its laminates, i.e., low density polyethylene (LDPE, #3), polycaproamide (N-6, #4), and biax-polypropylene (BPP, #5) for stiffness, tear, fold endurance and average thickness are given in Tables 7 and 9. In each case, the unflexed sample, whether in machine or in cross directions, would represent the properties of the paper or laminate as prepared (controls). The results listed for the flexed samples are those associated with some stress or deterioration of the samples. However, to provide some basis for comparisons, some data related to the tests here were provided by Mr. John Mercer, BEP, for currency papers, unprinted (UCP, #1a) and printed (PCP, #1b). The data associated with these currency papers also appear in Tables 7 and 9.

Paper is known to deteriorate more rapidly when flexed in the machine direction; while flexing in the cross direction produces only moderate changes in physical properties such as stiffness, tear resistance and fold endurance. Normally, paper is stiffer in the machine direction and more energy is required to bend the sample in the machine direction than in the cross direction. This result is also found in our tests for currency papers as well as the laminated samples of unflexed specimens. After flexing, the differential property deterioration of these samples again appears greater for the MD than in the CD, similar to currency paper.

a. Cantilever Stiffness and Thickness

The thickness of the sample is an important parameter of stiffness as well as for the other properties of currency papers and the laminates. This is readily shown when comparing the thicknesses of currency paper, UCP (#1a) and CPRT (#2). Printed currency paper (#1b) has a thickness smaller than unprinted currency paper due to processing conditions. Considering the differences in test properties between currency papers, UCP(#1a) and CPRT (#2), enclosing the CPRT in plastic does show improvements overall in going from CPRT (#2) through to BPP (#5). Covering currency paper (CPRT) with low density polyethylene (#3), a laminate in which the average thickness is the same as the original CPRT, the stiffness in the machine direction remains unchanged, while some changes were noted in the cross direction. The laminates of CPRT and N-6 (#4) produced samples of the appropriate thicknesses (114 μm). This sample (#4) is more stiff than the CPRT (#2) from which it was made, but less stiff, by a factor of 2.5 than the unprinted currency paper (UCP #1a) of comparable thickness. The BPP-CPRT laminates (#5) have stiffness values better than UCP (#1a) in the cross direction and almost as good in the machine direction. After flexing, the changes in stiffness values for the three laminates, LDPE (#3), N-6 (#4), and BPP (#5), are minimal while there are marked changes in the cross direction for UCP(#1a).

Most PCP (#1b) now in circulation is redeemed when the paper becomes limp or when most of its stiffness is lost(3,4). The point at which this limpness becomes apparent is about a value of 88 μN•m or below. Therefore any laminate not having an original stiffness factor considerably in excess of this value would be useless. On this basis, the stiffness data as shown in Tables 7 and 9, indicate the LDPE (#3), at least in its present form would be unacceptable as laminate material; BPP (#5) approaches PCP (#1b), in stiffness characteristics and N-6 (#4) appears in the marginal category. If the laminate is too stiff, bending and flexural properties become too cumbersome. On the other hand, sufficient stiffness is required for machine processing (pushing and pulling) of the final product laminate through the processing and dispensing equipment.

b. Elmendorf Tear Resistance

The property of propagating tear resistance (EL-TR) is, perhaps, one of the more important characteristics desirable in a good laminate. In this test, after the laminate is initially cut, whether in the MD or CD, the laminate must be able to undo the stress caused by the propagating front thereby stopping or delaying the tearing action at some point along the path of tear. Of the three laminates processed through the complete testing program, only N-6 (Tables 7 and 9, #4) has a tear resistance comparable to UCP (#1a) or PCP (#1b). LDPE (#3) and BPP (#5) laminates do not appear to afford additional resistance to tear once a tear has been initiated. Both N-6 (#4) and BPP (#5) are films having a coating of polyvinylidene dichloride (PVDC) in the 2-4 μm range. The difference in EL-TR values for these two films is due to the orientation of BPP film. This N-6 is not oriented. While biaxial (balanced) orientation does improve properties such as tensiles, etc., the EL-TR values decrease noticeably from the non-oriented PP(1). Similar observations were made for oriented N-6.

In a later section under test laminates, some laminates prepared from films having high tear resistance qualities will be reviewed.

c. Fold Endurance of Processed Laminates

The fold endurance test (MIT) data are also presented in Tables 7 and 9 for currency papers, (UCP, #1a, PCP, #1b) and CPRT (#2) and its laminates (LDPE) (#3), N-6 (#4), and BPP (#5). The results reported here for CPRT (#2), LDPE (#3), N-6 (#4), and BPP (#5) are averages of the first three samples in each series in the machine and cross directions. These samples in each series were run till breaks occurred. All other samples (7) in each series were run until the 5000 double fold cycles were completed. Three different MIT fold testers were used in these tests and all results fell within the averages as listed in Table 7 and 9. The immediate concern here appears to be the wide disparity between results from UCP (#1a) and CPRT (#2). CPRT (#2) being thinner than UCP (#1a) would be expected to have a higher fold endurance than its thicker counterpart (UCP). But the difference observed is a factor of 5 greater in the machine direction and a factor of 3-3.5 higher in the cross direction of CPRT (#2) over UCP (#1a). We have no ready explanation for this phenomena, unless, since CPRT (#2) is a specially prepared paper, the composition of this paper is not the same as UCP (#1a)

The fold endurance results for the laminate of LDPE (#3) and CPRT (#2) show little or no noticeable improvement in this important property over CPRT (#2) alone.

Data for the N-6/CPRT (#4) and BPP/CPRT (#5) laminates indicate a considerable enhancement in fold endurance for these laminates over both UCP (#1a) and CPRT (#2), whether flexed or unflexed, in either machine or cross direction modes. These results for fold endurance for N-6/CPRT (#4) and BPP/CPRT (#5) laminates were not unexpected since N-6 or BPP alone can survive more than 75,000 cycles without breaking.

The fold endurance data for these plastic-enclosed laminates, as shown in Tables 7 and 9, are far superior to UCP (#1a). Most flexible films, when available in the gauge thicknesses (13-18 µm) as required for this project, will probably possess this desirable property. Therefore, fold endurance of these and future laminates would not be a problem of major concern at this time.

VIII. Mechanical Properties of CPRT and Its Laminates

a. Mechanical Test Methods

The same procedures and equipment were used to determine the mechanical properties of CPRT and the laminates as were employed for testing research grade currency paper as reported previously(3,4,5,6).

1. Apparatus and Load Elongation Curves

An Instron Tensile Tester[1], model TM-M, was used to produce load-elongation curves from specimens 10 cm long and 1.5 cm wide while employing a crosshead speed of 1 cm per minute. The tensile properties of these specimens were determined according to procedures as outlined in Tappi Method, T 484-OS70(9). A typical load elongation curve for a

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[1] *cf, Disclaimer in Table 1.

research grade currency paper produced by this method is given in Figure 2(6). The data of interest for this project taken from the curves were breaking or tensile strength, elongation to break, energy to break, and the initial (Young's) modulus.

For paper testing, a number of conventional terms(5) are used to define the elastic, yield and plastic regions of the curves. The initial modulus is calculated from the initial stiffness which is derived from the slope of line AD in the elastic portion of the curve. The plastic modulus can also be obtained from the slope of the line DE which is taken in a region where the curve remains straight for a short distance. Since paper does not show a distinct yield point, the intersection of lines AD with DE is considered to be the load at yield and therefore, the distance OB is the elongation to yield and FG is the region of yield. The elongation to break is determined by the line OC and the energy to break is given by the area under the curve OEC. The area is determined by means of an integrator attached to the chart recorder. The breaking strength is read directly from the chart recorder at point E on the curve. Similar load elongation curves (fig. 3 (MD) and 4 (CD)) were obtained for CPRT and the laminates.

2. Edge Tear Resistance and Energy to Edge Tear

The edge tear resistance and energy to edge tear determinations were also performed on the same Instron Tensile Tester according to the Tappi Method, T 470-OS66(9). The results were obtained from specimens 10.0 cm long and 1.5 cm wide (fig. 1), and a crosshead speed of 1 cm per minute was used(12). The samples were torn at an angle of 20° from horizontal. The energy to edge tear was determined from the area under the curve by an integrator attached to the chart recorder on the tester.

IX. Discussion of the Mechanical Properties of CPRT and Its Laminates

a. Tensile or Breaking Strength

The data associated with the various mechanical test programs are presented in Table 8 for samples flexed in the MD and in Table 10 for those laminates flexed in the CD. Comparison data is also provided for unflexed control samples as well as for the currency papers, UCP and PCP. These test results are designed to evaluate several questions regarding these and future laminates from CPRT i.e., 1) How good or tough are these laminates prepared to date and, 2) How do they compare with UCP (#1a) and PCP (#1b)? Basically, the strength of the laminate will depend upon the properties of the substrate paper and the role of the plastic film and adhesive is to strengthen or reinforce the good qualities and to increase or improve marginal qualities. Since the films and adhesives are the minor components of these laminates, their contribution to the overall increase in mechanical properties of these laminates is more than encouraging. For example, considering the tensile strength of CPRT alone, the laminates N-6, (#4) and BPP (#5), yield breaking strengths as good as or better than UCP (#1a) in both MD and CD. The fact is further illustrated as shown by the curves in figs. 3 (MD) and 4 (CD) for unflexed control samples. After flexing, little or no change in tensile strength is observed. The laminates of N-6 (#4) and BPP (#5), are 20-25 μm thicker than CPRT (#2) and the LDPE laminate (#3) and this increase in thickness is reflected in larger breaking strengths of the former laminates. However, during some of the breaking strength tests, occasionally, the paper broke while the film was still intact. It is not known whether this was primarily due to poor laminate construction or to some other defect in the laminate.

b. Elongation and Energy to Break

The elongation to break and energy to break are measures of the distance the paper or laminate can be stretched before rupture occurs and in turn, the amount of work or energy required to produce this break at some distance. The relationship is usually in the same direction, i.e., small elongation to break percentages result in low energy needs to produce the break. In Tables 8 and 10, these results are listed for the currency papers, UCP (#1a), PCP (#1b) and CPRT (#2) along with data for the three laminates from CPRT. The low data values for CPRT (#2) alone, especially in the MD, indicate that this property would be difficult to improve in the final laminate. As shown in figs. 3 and 4, enclosing CPRT in plastic covers, does cause some improvement in the elongation in the MD, but the enhancement in elongation is best shown by the BPP (#5) laminate in the CD. Even so, the overall performances of these CPRT laminates in this category are unsatisfactory and they do not compare favorably for this property with the currency papers already in use.

c. The Initial Modulus

The initial or Young's modulus data are also given in Tables 8 (MD) and 10 (CD). As mentioned earlier, the initial modulus is derived from the slope of the line AD as shown in fig. 2 and from similar lines drawn in figs. 3 and 4. For unflexed samples, the initial modulus is a factor of 2 larger in the MD than in the CD. Since stiffness is directly related to the initial modulus as the modulus changes, the stiffness also changes, usually in the same direction, for flexed samples(13). The slope of the lines AD in figs. 3 and 4 for the laminate BPP (#5) and N-6 (#4) are slightly larger than for CPRT (#2) and the LDPE laminate (#3) which results in the stiffness also being greater. However, the cross-sectional areas of these former laminates are also larger due to their increased thickness. This factor results in the near equivalency of the moduli among the four specimens in either MD or CD. For specimens flexed in the MD, the decrease in the initial modulus is more severe in the MD while samples in the CD show a slight increase in the modulus brought about by a slight increase in stiffness and a decrease in the thickness. Flexing the samples in the CD, produces very little change in the initial modulus. Any change in the stiffness is simply off-set by a corresponding change in thickness of the sample. Since the initial modulus for CPRT (#2) and the laminates, LDPE (#3), N-6 (#4) and BPP (#5), are nearly equivalent in either MD or CD, the contributions from the plastic films to the initial stiffness factor of the laminates would be minimal and most or all of the stiffness of these laminates is wholly dependent upon the CPRT itself.

d. Edge Tear Resistance and Energy to Edge Tear

Generally, edge tear resistance (ED-TR) and subsequently, energy to edge tear values are usually much higher than those values for Elmendorf tear resistance. In ED-TR, the paper, film or laminate is not split prior to testing and as a result, all of the energy must be expended in causing the tear. The results for UCP (#1a), PCP (#1b), CPRT (#2) and the laminates (#3,4,5) are given in Tables 8 (MD) and 10 (CD). Again, the data show a marked improvement in values for BPP (#5) laminate over CPRT (#2). This result is one of the more advantageous contributions that a plastic film can provide to a laminate. No data is available at this time for CPRT comparison with currency papers, UCP or PCP in this category.

X. Summary of Test Results

The complete physical and mechanical property test determinations are reported here for CPRT (#2) and three laminates prepared from CPRT, namely, low density polyethylene (LDPE, #3), polycaproamide (N-6, #4) and biaxially-oriented polypropylene (BPP, #5) and where possible, comparisons were made between the currency papers, UCP (#1a), PCP (#1b) and CPRT (#2) and the laminates. The main effect of enclosing CPRT in a plastic film laminate, such as BPP or N-6, is to produce a product of superior fold endurance than any of the currency papers listed in Tables 7 and 9. None of the laminates tested to date have better properties in "all" categories of concern than the currency papers now in use. Overall, the CPRT-BPP laminate (#5) exhibited more favorable properties in more categories than did either N-6 (#4) or LDPE (#3) when compared with the currency papers, UCP (#1a) or PCP (#1b). However, the BPP laminate also suffers from a low Elmendorf tear resistance. Although N-6 laminate shows Elmendorf tear resistance values as good as the currency papers, the cantilever stiffness and edge tear resistance values for this laminate are much lower than BPP. The low elongation to break values inherent in the CPRT especially in the MD are also apparent in the laminates in the MD. Although values for this property increase almost by a factor of two for BPP in the CD, it is doubtful whether the elongation to break in the MD can be sufficiently upgraded to produce an acceptable laminate from CPRT using the plastic film thickness (12.7 µm) envisioned for this project. For this reason, due to the poor performance values for CPRT, emphasis for this project shifted from testing CPRT-based laminates to the testing of all polymeric synthetic papers as possible currency substrates.

XI. Physical Properties of Test Laminates Prepared From Various Plastic Films and CPRT After Flexing

While awaiting the arrival of the synthetic polymeric papers for testing, some physical property measurements were determined for the samples prepared in Tables 4 and 5. The results of these tests are given in Table 6, for cantilever stiffness (CS) and Elmendorf tear resistance (EL-TR) after the specimens were flexed in either MD or CD. These samples were tested in order to determine the effects of the film, adhesive and thickness of the laminate upon these properties.

a. Biax-Polypropylene (BPP) and Polyvinylidene Dichloride (PVDC)

In Table 6, EL-TR data are listed for test laminates of uncoated BPP, (A1) and polyvinylidene chloride (PVDC, regular film, A7). In these two cases, the CPRT was coated with an adhesive specially designed for polypropylene. The adhesive is a chlorinated, low molecular weight polypropylene (Table 2 #12) and when dry, a flexible, almost colorless film is formed which requires heat activation for bonding. The EL-TR values for these laminates (A1, A7) are about the same order of magnitude as the CPRT alone or the BPP/CPRT laminate (Table 7, #5). Even though some improvement in EL-TR is shown for the adhesively bonded test sample of BPP, (A1), the increase was not great enough to warrant further work with BPP and PVDC films.

b. Nylon-6 (N-6) and Polyethylene Terephthalate (PET)

Biaxially oriented films having the same thickness as non-oriented Nylon-6 (N-6) usually have average tear resistance values lower than N-6 (Compare Table 6, A, BPP #1 and PVDC, #7). However, a comparison of the EL-TR data for laminates, biax-PET/CPRT, (Table 6, A3), and N-6 (Table 6, A2) with N-6 (Table 7, #4) (these laminates have about the same thicknesses) show that the EL-TR values of the PET laminate is better in the MD and of comparable value in the CD. Both of the former laminates were bonded with an vinylacetate-ethylene adhesive (VAE) (Table 2, #4). Yet for the two N-6 laminates, the adhesive bonding, though different in both cases (VAE vs PVDC), had essentially no effect upon the EL-TR values for the N-6 laminates. Interestingly, the laminates prepared earlier from a coated (PVDC) PET, all delaminated during the flex testing program; an indication that additional adhesion is necessary to prepare stable laminates from PET and CPRT. A thicker version of the PET/CPRT laminate, (Table 6, A4), gives excellent EL-TR values, but its thickness may also increase stiffness and decrease fold resistance to an unacceptable range.

c. Polyvinyl Chloride (PVC)

Two test laminates were made from PVC and CPRT. One sample (Table 5, A5) was prepared by compression molding while the other (Table 6, B1) was made by roll lamination. Both samples survived the machine flexing test without creasing or delamination. There is a considerable difference in thickness (43 µm) between the samples due to the adhesive applications. This difference in thickness is reflected in the test properties for cantilever stiffness (CS) and Elmendorf tear resistance (EL-TR) values. Sample (B1) shows excellent EL-TR values, but would appear to be too stiff for practical purposes of handling and folding. The values for PVC sample (A5), somewhat thinner, are in the acceptable range when compared to currency papers, unprinted (UCP, #1a) and printed (PCP, #1b) in Table 7. This PVC film is a high gloss variety and high gloss films are prone to develop blocking problems. Stability problems toward UV light (sunlight) would also be suspect without incorporation of UV inhibitors into the final film.

d. Polyvinyl Fluoride (PVF)

Although PVF film (A6) contains a fluorine atom on the polymer chain, no special adhesives are required to bond the film to CPRT. After flexing, some edge delamination occurred and the test results shown in Table 7 (A6), were performed from samples cut from the stable interior part of the laminate. The values for CS and EL-TR, although slightly low, would be in the acceptable range. PVF does have good abrasion and sunlight resistance as well.

e. Copolymer of Ethylene and Chlorotrifluoroethylene (E-CTFE)

For the copolymer, E-CTFE, the lowest film thickness available at this time is 25.4 µm (1.0 mil). The test measurements, listed in Table 6 (B2), are from a sample which was prepared by roll lamination but was not flexed in either MD or CD. For all of the E-CTFE-CPRT laminates, after flexing, the surfaces of the films became very rough and ribbed, i.e., the film surface creased and raised slightly, perpendicular to the direction of flex. This distortion of the film surfaces occurred whether or not the laminates were flexed in the CD or MD. To allow for complete curing of the adhesive, some samples were flexed at 7 and 14 days intervals after preparation. The flex results were identical. A single sided film - CPRT laminate was prepared for flex testing. After seven days of aging, the laminate was flexed. The sample was first flexed with the film side down on the roller, then flexed again in the reverse position. No signs of creasing or ribbing were evident on the surfaces of this single sided laminate after this treatment. The cantilever stiffness value for the unflexed sample does not indicate that the laminate is inherently too stiff to cause this flex creasing. Increased stiffness of the laminate could lead to stress cracking phenomena under flexing conditions. We have also observed this type of "ribbing" or cracking of the film surfaces during flex testing of polyester (PET) laminates. The Elmendorf tear resistance values for this laminate (B2) are excellent and when these values are compared with the currency paper (Table 7, #1a and #1b) data, E-CTFE (B2) is found to be far superior in this property.

f. Copolymer of Ethylene and Tetrafluoroethylene (E-TFE)

Only limited quantities of film, E-TFE, were in stock in thicknesses of 12.7 and 25.4 µm. The test results for cantilever stiffness and Elmendorf tear resistance for these laminates are listed in Table 6, (B3, 12.7 µm) and (B4, 25.4 µm). The data were obtained from samples flexed in the MD. The thinner laminate (B3) survived the flex test without "ribbing" and no rough spots developed on the surfaces of the films. However, some thin lines could be seen occasionally in the laminate after flexing, but these (lines) seem to be located on the bonded interior side of the second film (backside). The lines do not appear to be detrimental to the flexed film. The thicker sample (B4) shows more creases than did the thin laminate, but certainly not as much as was observed with E-CTFE (B2). The cantilever stiffness (CS) values for the thin E-TFE-CPRT laminate (B3) are lower than the values anticipated for a laminate of this thickness (152.4 µm). The test laminate (B4) has better CS values but the laminate is simply too thick for practical purposes.

Both laminates exhibit excellent EL-TR values; in fact for sample (B4), we were unable to tear the laminate with the existing EL-TR equipment on hand.

g. Tyvek-1058 (Manually Coated)

Two of the coated Tyvek-1058 samples (B5) and (B6), listed in Table 6, were flexed in the CD while the third sample (B7) was flexed in the MD. For Tyvek-1058, the MD was assumed to be in the direction taken by the swirls of fibers in the film and again appeared to be the short side of the sheet. After flexing, there were no signs of the coating peeling from Tyvek-1058. The distinquishing feature among the samples is the thickness of the coating. All three specimens still maintained excellent EL-TR values after flexing when compared to uncoated Tyvek-1058 as listed in Tables 7 and 9, (#6). As also it can be noted in Tables 7 and 9, the cantilever stiffness values of the uncoated Tyvek-1058 decrease markedly in the direction of the flex from those values associated with the unflexed samples. One coated sample of Tyvek-1058, Table 6, B6, appears to reverse this trend. However, since these samples in Table 6 are only preliminary samples, not statistical samplings as those listed in Tables 7 and 9, the trend towards better cantilever stiffness for a coated Tyvek-1058 can only be taken as an indication that improvements in CS values are possible.

h. Coated CPRT

The physical test results for coated CPRT after flexing are given in Table 6, (B8) and (B9). Basically, a slight enhancement of the EL-TR values was noted from that of the uncoated CPRT (Table 7, #2) but no significant increases were observed in the CS data even though the thickness of these test samples approach those of UCP (Table 7 #1).

Part B: Synthetic Polymeric Papers

Some synthetic polymeric papers may be better suited as alternatives for use as currency papers than are laminated materials. For laminated papers, after cutting the sheet into pieces of proper size for currency use, three types of edge materials are left exposed to the atmosphere and surroundings, the paper, the adhesive and the plastic film. Unless some means were provided to seal those edges after cutting, routine wear and tear, and exposure of these edges to any hostile environment probably would cause delamination of the plastic film. With synthetic papers after cutting, these problems are avoided because the entire surface area is virtually identical. Since synthetic papers vary greatly in composition and structure as well as in preparation, the defects that are found are usually inherent in the paper itself rather than in any edge effects.

I. Classification

In the past, synthetic papers were also called "plastic" paper. In recent years, some efforts have been made to distinguish synthetic papers from plastic papers(14). The classification is based loosely up on the method of preparation and the eventual end market use of the paper.

a. Synthetic Papers

Synthetic papers are classified into categories based on: (a) extruded plastics film, (b) synthetic fibers and (c) spunbonded products. In group (a), the extruded plastic film receives a post-extrusion treatment of either a coating material or incorporation of inorganic additives to make the plastic film resemble paper in appearance and texture. For group (b), synthetic fibers can be used alone or in combination with conventional paper pulp to produce synthetic paper by the usual paper-making processes. In group (c), the synthetic papers are prepared from synthetic strands of polymer, spun into interconnected fibers and finally, bonding of the fibers together into sheets under heat and pressure.

Synthetic papers based on the above classification are more allied with typical paper products and therefore these papers are geared for printing and writing paper markets of the graphics industry.

b. Plastic Papers

Plastic paper, in general, does not require any post extrusion treatment and the product is used mainly in the packaging industry as a substitute for various paper bags, wraps and decorative functions.

II. Physical Properties of Synthetic Papers

Polymeric sheet materials were obtained from the Bureau of Engraving and Printing (BEP) in order to compare their physical and mechanical properties with the currency papers, unprinted (UCP), and printed (PCP), as well as with the laminates prepared for this project. The following sheet materials were obtained from BEP for this purpose: 1. Tyvek-1058, 2. Nomex-410 and -414, 3. Texoprint, and 4. Melinex-377 and -442. Based on the classification discussed in the preceding sections, Tyvek-1058, Nomex-410 and -414, and Texoprint are synthetic papers. The hand and texture of this group resemble conventional paper. Melinex-377 may be typed as a plastic paper, destined for the decorative market while Melinex-442 is simply a clear, plastic film, not classified as either a synthetic paper or plastic paper. Both Melinex samples were tested for internal purposes within BEP.

In general, the synthetic papers were tested in the same fashion, using the same equipment as discussed earlier for currency paper (reduced thickness, CPRT) and the laminates prepared from CPRT. Again, thirty samples from each paper were cut from sheets in both the MD and CD as well as the samples needed for unflexed control data also in the MD and CD. Standard test conditions of 23 °C and 50% relative humidity were employed for all samples. The results of the physical test programs are given below.

a. Tyvek-1058

Tyvek is prepared from high density polyethylene by first spinning continuous strands of interconnected fibers and bonding these fibers together into sheets under heat and pressure(15). The process produces a paper that has a fiber-swirl pattern, is white and opaque, and has smooth surfaces. Since Tyvek is made from a high density polyethylene base, the chemical and physical properties of the paper would be expected to be similar to the base polymer. Tyvek is inert to most acids, bases, and salts. It is unaffected by water, but it will swell in some organic solvents which may cause some problems with solvent based printing inks. Prolonged exposure to ultraviolet (UV) light causes a decrease in property values. Tyvek maintains good flexibility at low temperature (-73 °C but begins to shrink at 118 °C and will melt at 135 °C. It is sensitive to tension-caused width loss and deformation increases at elevated temperatures (~ 107 °C). Pressure also causes shrinkage of Tyvek.

The physical properties of Tyvek-1058 are given in Table 7, (#6), for those samples flexed in the MD and in Table 9, (#6), for those samples flexed in CD. In both cases, flexed samples are again compared to the unflexed control samples. The data for the laminates prepared earlier as well as data for UCP (#1a), PCP (#1b) and CPRT (#2) are also presented in Table 7 and 9, for comparison purposes with the polymeric papers.

The results from the cantilever stiffness (CS) measurements of Tyvek-1058 indicate that before flexing, this sample is about as stiff as the N-6 laminate (#4), but not as stiff as UCP (#1a) or the BPP laminate (#5). After flexing Tyvek-1058, the cantilever stiffness values decrease markedly, well below the acceptable level, in the direction of the flex whether MD or CD. The CS values for those samples perpendicular to the direction of flex show some stability in the CD when flexed in the MD, but a 30% drop in CS values occurs in MD when flexed in CD. Both unflexed values are still above the acceptable range of 88 μN•m. When flexing Tyvek-1058 in either direction, some samples showed crease formation along the line of flex. At present it is not known whether these creases are related to Tyvek's sensitivity to tension caused width loss.

The Elmendorf tear resistance data (EL-TR) are also presented in Tables 7 and 9 (#6). Due to the fiber-like swirls in the sheet, Tyvek-1058 is very difficult to tear in a clean fashion even when pre-cut. The tearing action under these conditions appears to mushroom the top layer in front of the tear making it more difficult to continue, until finally some of the top layers simply shear off on either side of the advancing front. The EL-TR data for Tyvek-1058 show that it is as good as the fluorocarbon-CPRT laminates (Table 6, B2, B3, B4) in this respect.

The MIT fold endurance for Tyvek-1058 is excellent and at this thickness (168.9 μm), it rivals some of the thinner laminates listed in Tables 7 and 9.

b. Nomex-410 and -414

Nomex is an aromatic nylon or polyaryl amide type of polymer. The sheet is formed from short polymeric fibers (floc) and fibrous binder particles by normal papermaking processes(16). The sheet contains no other fillers or binders. Calendering the paper at high temperatures and pressures bonds the constituents together to form the sheet.

Nomex sheet is tawny colored. The surfaces are not as smooth as those of Tyvek and the hand of Nomex is harsh. Nomex will not melt or support combustion in normal atmospheres, and has high resistance to deformation. It is generally insoluble, compatible with various oils, and resistant to chemical and radiative degradation. Water acts as a mild plasticizer for Nomex paper and at 50% relative humidity, Nomex retains 4-5% of moisture depending upon the thickness of the paper.

The physical properties of Nomex sheets are listed in Table 7 (#7, 8 and 9) for specimens flexed in the MD and in Table 9 for CD samples. The Nomex sheets tested were; 410-4 (119.9 µm), 410-5 (139.2 µm) and 414 (100.1 µm). The numbers 4 and 5 after the Nomex 410 samples simply refer to the nominal thicknesses of each sheet before conditioning and the numbers aid in distinquishing the two sheets during discussion of their properties.

Nomex-414 (#9) is too thin and lacks sufficient stiffness before and after flexing to be of any interest as a possible currency substrate by itself, but it was tested as a future prospect for coating or for adhesive laminations with other films to improve its properties.

The main difference between Nomex-410-4 (#7) and 410-5 (#8) is in the thicknesses (~ 20 µm) of the samples. The greater thickness of the Nomex-410-5 (#8) samples is reflected in better overall physical properties of the latter sheet. For unflexed samples, Nomex-410-5 (#8) has better cantilever stiffness values than does the currency papers (UCP #1a and PCP #1b) in either MD or CD. After flexing, Nomex-410-5 (#8) retains most of its stiffness characteristics in each direction when flexed in MD. The major loss of stiffness for Nomex-410-5 occurs in the CD when flexed in the CD. The remaining stiffness of this latter sample is still greater and well above the required minimum values than any of the currency papers and CPRT laminates except for the BPP laminates (Table 7, #5).

The Elmendorf tear resistance (EL-TR) values given in Tables 7, (MD) and 9, (CD) for the three Nomex samples tested, indicate that these samples are superior to the currency papers (#1a and #1b) and the laminates to propagating tear resistance. For Nomex-410-5 (#8), whether unflexed or flexed in either direction, the CD fraction of sample exhibits better EL-TR values than does Tyvek-1058 (#6). The Nomex samples show little change in EL-TR value after flexing in either MD or CD. Surprisingly, the differential thicknesses among the three samples have a smaller than anticipated effect on the EL-TR value in the MD of the samples. EL-TR values more akin to the CD data were expected and the difference in value may be due to the alignment pattern of the fibers in the MD. The Nomex samples tear more cleanly in this test than did Tyvek-1058, but a small amount of top layer shearing during the process was also observed.

The MIT fold endurance data provided in Tables 7 (MD) and 9 (CD), place the three Nomex samples in the acceptable range (> 5000 double folds in each direction) on par with currency papers, UCP (#1a) and PCP (#1b) but well below the fold endurance for Tyvek-1058 (#6) and the laminates (#3, 4 and 5).

c. Texoprint

Texoprint(17) is prepared from bleached kraft fibers which is formed into a low density absorbent sheet. The sheet is then treated with an elastomeric polymer latex and opacifying fillers. The dried sheet is coated on both sides with printing fillers, notably titanium dioxide and a flexible latex binder. In this process, the usual cellulosic fiber base is replaced by the polymeric latex. The starches, glue and casein binders in the coating are all replaced with synthetic resins. On this basis, Texoprint is classified as synthetic paper rather than the conventional cellulosic paper.

The physical properties of Texoprint synthetic paper are listed in Tables 7 (#10 MD) and 9, (#10 CD). Texoprint paper has the highest cantilever stiffness value in the unflexed MD of all the samples tested to date and ranks second in the CD behind Melinex-377 (#11). After flexing, there is a considerable decrease in these values in the direction of flex. The residual stiffness after flexing is still above minimum values of 88 μN•m.

Unfortunately, Texoprint paper falls well below the minimum requirements for fold endurance (> 4000 double folds in each direction) and it has the lowest fold endurance of any of the samples listed in Tables 7 and 9. The Elmendorf tear resistance of Texoprint paper is equivalent to currency paper (#1a) and the N-6 laminate (#4), but it is somewhat low for a synthetic paper of this thickness (154 μm).

III. Physical Properties of Plastic Paper and Film

a. Melinex-377 and -442

The Melinexes(18) are polyester type films based on the polymer, polyethylene terephthalate (PET). These films are biaxially oriented and shrinkage (up to 3%) will occur at exposure to high temperatures (190 °C). Melinex-377 is a white, translucent matte film with low surface gloss destined for the decorative markets. Melinex-442 is a transparent film of high clarity suitable for general purpose applications.

The physical properties of the Melinex-377 (#11) and -442 (#12) are given in Tables 7 (MD) and 9 (CD), for both the unflexed and flexed samples. Melinex-377 (#11) has excellent values for cantilever stiffness, Elmendorf tear resistance and fold endurance. Ater flexing, these values are retained essentially unchanged. Melinex-442 (#12) has acceptable stiffness characteristics and excellent fold endurance but the film lacks the required Elmendorf tear resistance (> 1000 mN) as well as the proper thickness (~ 115 µm).

These films, Melinex-337 and -442, were not designed for currency paper substrates.

IV. Mechanical Properties of Synthetic Polymeric Papers

For the determinations of the mechanical properties of the synthetic papers, the same tensile tests and procedures were employed that were used to obtain the mechanical properties of currency paper (CPRT) and the laminates prepared from CPRT. Again, the standard calibration conditions of 23 °C and 50% relative humidity were adhered to for these tests.

The mechanical property data can be found in Table 8, for those samples flexed in MD and in Table 10, for those specimens flexed in the CD. From the data in these tables, property comparisons can be made from among the currency papers (#1a and #1b), CPRT (#2), the CPRT laminates (#3, 4, 5), the synthetic papers (#6, 7, 8, 9, 10), and the plastic films (#11 and #12).

Load elongation curves are shown in figure 5, for the above control samples from the synthetic papers and films cut in the MD and in figure 6, for those unflexed control specimens cut in the CD. The curves were reconstructed on a 50 kg full scale load basis in order to accommodate all the curves on the same graph.

Standard sample sizes (cf., fig. 1, 10 cm x 1.5 cm) were used for testing the mechanical properties of the synthetic papers (#6 to 10). For the Melinex films (#11 and #12), due to their extensive elongations, samples having 5 cm span lengths were employed in the tensile tests. the cross head speed of the tensile test for all samples was 1 cm/minute.

a. <u>Tyvek-1058</u>

The breaking strength of Tyvek-1058 (#6), is in the acceptable range for a currency substrate material and this property is retained substantially unchanged after flexing in either MD or CD. Although polyethylene is considered to be an extensible polymer, Tyvek-1058 did not "neck down" before breaking. The break was fairly clean and little evidence of shear was observed.

Tyvek-1058 has the largest elongation to break (%) values of the three types of synthetic papers as well as the currency paper and laminates. Only the Melinexes have larger values. This property of Tyvek-1058 does not decrease materially with flexing in either direction.

The unflexed sample stretches slightly more in the CD before breaking than in the MD. When flexed in the MD, there is a small decline in elongation values for both MD and CD samples, while CD flexing causes a slight increase in elongation results.

The energy requirements to elongate Tyvek-1058 samples to the break point are proportional to the elongation; the more the sample elongates, more energy is required to produce the break whether the sample was flexed or not in either MD or CD. Almost all of the required energy is expended in the plastic regions of curves in fig. 5 and 6.

Unflexed Tyvek-1058 has better edge tear resistance values than for any of the other synthetic papers listed in Tables 8 and 10. Only the CPRT-BPP laminates (#5) and Texoprint (#10) have better edge tear resistance. When Tyvek-1058 is flexed in the MD, a 46% loss of edge tear resistance occurs only in the CD portion of the sample, while flexing the sample in the CD, major loss of edge tear resistance occurs in both MD and CD. The large energy to edge tear values associated with unflexed Tyvek-1058 sample, may be due to its ability to elongate and crease before it tears.

The initial modulus is a measurement of the resistance to deformation a material possesses in the elastic region of the load elongation curve as shown in fig. 2.

Tyvek-1058, similar to conventional paper as also shown in fig. 2, does not have a definite yield point (cf., figs. 5 and 6) and little energy is required to reach the yield region in either the MD or CD as the applied load traverses through the elastic portion of the curve. The exceptionally low initial modulus for Tyvek-1058 is due to its low initial stiffness coupled with the large cross-sectional area associated with the thickness (169 µm) of the material. The average initial stiffness for unflexed Tyvek-1058 is: MD = 112 kg or 1097.6 N, and CD = 123 kg or 1205.4 N. When Tyvek-1058 is flexed in the MD, the initial stiffness factor (slope of line AD - fig 5) for the MD portion of the sample is decreased further by 46%, while relatively no change was observed in the CD segments. After flexing Tyvek-1058 in the CD, both MD and CD portions of the samples undergo considerable change in initial stiffness; the retention of the property is again less (57%) in the direction of flex. Some changes in the thickness values of Tyvek-1058 were also noted after flexing. Since the initial modulus is derived from the slope of line AD (fig. 2) and the thickness of the sample, changes occurring in either of these parameters after flexing also affects the value of the initial modulus.

b. Nomex-410-4, -410-5 and -414

Data for the mechanical properties of the Nomexes, 410-4 (#7), 410-5 (#8) and -414 (#9) are listed in Tables 8 (MD) and 10 (CD). These data were again obtained from load elongation curves as illustrated in figs. 5 (MD) and 6 (CD) for unflexed control samples.

Unlike Tyvek-1058, the three Nomex samples tested are generally stronger mechanically in the MD than in the CD. After flexing in either the MD or CD, this result (MD > CD) still persists. The differences in property values of the Nomexes between the MD and CD as given in Tables 8 and 10 are readily discernible after comparing the curves in figs. 5 (MD) and 6 (CD). For unflexed samples the extrapolated yield point (cf., fig. 2) for Nomex-410-5 (#8) is approximately a factor of 2 greater for the MD over the CD and this difference does not decrease substantially after flexing in either directions. Essentially, the energy required to stretch the sample through the elastic yield region is twice as great for the MD as it is for the CD. Although the elongations to the break points are good in either direction for Nomex-410-5 (#8), the energy needed to cause the break (area under the curve) is much greater in the MD again because of the two-fold increase in the energy requirements in the elastic portion (line AD) of the load elongation curve. Most of the total deformation (elastic plus plastic, line OC) occur in the plastic region of the curve.

After flexing Nomex-410-5 in the MD, there is a decrease (8%) in the breaking strength of the MD portion of the sample while no change in value occurred in this property in the CD. The decrease in breaking strength in the MD is also accompanied by a drop in values for elongation to break (21.5%) and the energy to break (28%). The property values retained by the Nomex-410-4 (#7) and -410-5 (#8) for these categories after flexing in the MD or CD are still considerably higher than most of the currency papers, laminates and synthetic papers as listed in Tables 8 and 10.

The initial moduli of Nomex-410-4 (#7) and -410-5 (#8) are lower than CPRT (#2) and the laminates (#3, 4, 5) in either the MD or CD but not as poor as Tyvek-1058 (#6) when the Nomexes (#7 and #8) are compared with printed currency paper (#1b) in the MD and especially in the CD. The largest decrease (22%) in the modulus of these samples occurs for Nomex-410-5 (#8) in the CD after it was flexed in the CD. The decrease in the modulus is attributed to the decrease in the slope of the line (AD) in the elastic region of the elongation curve (fig. 6, CD) which causes a decrease in the initial stiffness parameter (4900 to 3822 N). However, the initial stiffness for Nomex-410-5 (#8) retained is still a factor of 5 greater than Tyvek-1058 ((#6), 686 N) under similar flexing conditions. When flexed in the MD, Nomex-410-5 (#8) undergoes the least change (<8%)

in moduli in either direction. Although the values for the initial moduli of unflexed Nomex-410-4 (#7) are equal to the values for Nomex-410-5 (#8) the moduli of the former also decrease (17%) in the direction of flex whether MD or CD.

The data for edge tear resistance and the energy required to cause the tear for the Nomexes are provided in Tables 8 (MD) and 9 (CD). For unflexed samples, Nomex-410-5 (#8) has edge tear resistance values comparable to Tyvek-1058 (#6), but much lower values than the BPP/CPRT (#5) laminate. When the samples are flexed in the MD, Nomex-410-5 (#8) loses from 9% (MD) to 15% (CD) of its edge tear resistance while Nomex-410-4 (#7) shows an increase in edge tear resistance from 12% (MD) to 42% (CD). Only Nomex-410-5 (#8) shows any loss of edge tear resistance (MD, 12%) after flexing the samples in CD, but Nomex-410-4 (#7) yields an equal (8%) but smaller amount of increase in both MD and CD. The energy requirements needed to produce the edge tear in the Nomexes also vary accordingly as the amount of the edge tear resistance changes after flexing as shown in Tables 8 (MD) and 10 (CD).

c. Texoprint

The mechanical properties as determined for Texoprint synthetic paper are given in Tables 8 (MD, #10) and 10 (CD, #10). Load elongation curves for unflexed samples of Texoprint are also shown in figs. 5 (MD) and 6 (CD). For unflexed samples, Texoprint (#10) has average breaking strength values in the MD but much lower values in the CD for a synthetic paper of this thickness (~ 154 μm). The values for the breaking strengths do not change significantly after flexing in either direction.

As shown in fig. 5 (MD), Texoprint has the lowest elongation to break values in the MD of any of the synthetic papers tested; ranking only above the laminates in this property. The CD portions of the unflexed samples have elongation to break percentages comparable to Nomex-410-4 (#7) but with much lower energy to break requirements. When Texoprint (#10) is flexed in the MD, there is a slight increase in the elongation to break in both MD and the CD, but the energy needed to produce the break decreased in both directions from that of the unflexed samples. Texoprint is the only sample tested in which this occurrence was observed.

The initial modulus for unflexed Texoprint (#10) samples is comparable to the Nomexes and Melinexes in the MD but considerably lower than either of these papers in the CD. Flexing Texoprint (#10) in the MD causes a severe drop in the initial stiffness (8732 → 3420 N) in the MD; and as a result, only 38% of the initial modulus is retained. The CD portion also suffers from a decrease, but smaller, in stiffness resulting in a 66% modulus retention value. The MD flexed Texoprint also shows the largest changes in thicknesses (increases) of any of the samples tested. The major change in the initial modulus of Texoprint, flexed in the CD, occurs in the CD as only 56% of the modulus value is retained while 81% of the MD modulus is still intact. Only a slight change in thickness of the CD sample was observed under these conditions.

The edge tear resistance of unflexed Texoprint (#10) can be placed in the same category as Tyvek-1058 (#6) and Nomex-410-5 (#8) for the MD region, but Texoprint is far superior to these papers in the CD; only the BPP/CPRT (#5) has better values for edge tear resistance but less energy is necessary to produce the edge tear in this laminate.

V. Mechanical Properties of Plastic Paper and Film

a. Melinex-377 and -442

The mechanical properties of Melinex-377 (#11) and -442 (#12) are listed in Tables 8 (MD) and 10 (CD). The data were again calculated from the load elongation curves as shown in figs. 5 (MD) and 6 (CD) for unflexed control samples. As stated earlier, the Melinexes are not classed as synthetic papers but more properly as plastic films. The differences between the two species can be readily observed by comparing the various load elongation curves in figures 5 and 6. Unlike the synthetic or conventional papers, the region of yield is much smaller and a more definite yield point can be calculated for the Melinex samples. The "humps" in the curves slightly past the yield region are due to the Melinex samples "necking down" as it enters the plastic region. Both Melinex samples undergo extensive elongation (MD > CD) in either direction requiring a large amount of energy to cause the break. When the Melinexes (#11, 12) are flexed in the MD, no significant changes occur in the property values in either the MD or CD. However, after Melinex-337 (Table 10, #11) is flexed in the CD, all of the CD samples experience "jaw breaks" on the tensile tester and no data for the CD could be obtained. No problems of this type were encountered for the MD portion of the sample. The flexing of Melinex-442 (#12) in either MD or CD causes white lines to appear at or near the edges of the samples perpendicular to the direction of the flex. The lines extend inward from 1 to 2 cm. Since the Melinexes are biaxially oriented, the applied stress (flexing) may have disrupted the orientation locally allowing some segments of the polymer to crystallize. The lines appear to be located internally in the film as the surface was still smooth to the touch. Melinex-377 (#11) is white and opaque and it could not be determined whether similar stress lines appeared after the samples were flexed in either direction.

Part C: Discussion of Test Results and Recommendations

I. Currency Paper (Reduced Thickness) and Its Laminates

From the beginning of this project, three assumptions were made: (1) the currency paper of the laminate would be printed on both sides before the lamination process occurred; (2) the nominal thickness of the end product laminate would be equal to the printed currency paper (115 µm or 4.5 mils); and (3) the property values as given in Table 7, 8, 9 and 10 for the currency papers (#1a and #1b) would be used as the minimum values acceptable for a currency paper substitute (laminate or synthetic paper) both before and after flexing. In this latter case, not all of the data associated with the currency papers were available as shown by the data gaps in the tables. However, sufficient data is available for the currency papers in most of the critical categories to provide a basis for comparisons.

To compensate for the thicknesses of the outer plastic film covers and adhesives of the laminate, a special currency paper (CPRT, #2) was used for this project that was about 30 µm (25%) thinner than the unprinted currency paper (#1a). The printing of currency paper causes about a 8 µm decrease in the thickness (to ~ 115 µm) of the printed currency paper as measured from fresh, uncirculated one dollar Federal Reserve notes obtained from a local bank. Printed currency paper undergoes two compressions during printing, but the laminate would have to sustain three, i.e., printing and laminating. For this reason, plastic films having thicknesses between 12.7 and 25.4 µm could be employed depending upon the thickness of the applied adhesive. Plastic films, when applied below their softening points, are relatively incompressible.

The reduction (25%) in the thickness of the currency paper (#1a) to the thickness of the currency paper (#2) used for this project causes considerable changes in both the physical and mechanical property values for CPRT (#2) in both the MD and CD. Only the MIT fold endurance and initial modulus show any increase in property values; all of the other categories listed yield lower values than sample #1a. The role of the plastic outer covers and adhesives of the laminate is to provide increased protection and durability for currency paper by improving the overall characteristics, both physically and mechanically of the currency substrate (CPRT, #2) sufficiently above the data values for unprinted currency paper (#1a). Larger values are not necessarily better values, but a equitable ratio of property values between the MD and CD with at least 90% retention of property values after flexing was sought. As shown in Tables 7 to 10, CPRT (#2) has serious physical defects in cantilever stiffness, especially in the CD, and Elmendorf tear resistance, and mechanically in elongation to break and edge tear resistance. Of these properties, the exceptionally low elongation to rupture in the MD is the most detrimental to the paper and also the most difficult defect to overcome by lamination. The lamination of CPRT (#2) with biaxially oriented polypropylene results in a laminate (#5) which has better property values than does the unprinted currency paper (#1a) with respect to fold endurance, breaking strength, and edge tear resistance. Improvement was also noted in cantilever stiffness with excellent retention of values after flexing in both MD and CD. The elongation to break percentage almost doubled in the CD and these values were maintained after the samples were flexed in either direction. The small increase in the elongation to break values in the MD and the low Elmendorf tear resistance of this BPP-CPRT laminate (#5) would be sufficient cause to reject biax-polypropylene as a laminate material.

The N-6-CPRT laminate (#4) does exhibit good Elmendorf tear resistance and fold endurance, but it, too, suffers from low cantilever stiffness especially in the CD and again in the elongation to break and edge tear resistance values.

A study of the overall property results of the lamination of currency paper (#2) with plastic films (#4, 5) indicate that the process can produce a laminated substrate with generally better properties than the paper stock from which it was made. Only a relatively few combinations of plastic films and adhesives from the myriad of material available were investigated in this project. Plastic films having superior property values may eventually emerge in the market place but the ideal plastic film laminate may be a compromise among the excellent, good and average property values of the various categories listed in the tables. The currency paper stock, used in the lamination, would have to be strengthened in many categories especially in elongation to yield and break points. These are two mechanical properties that cannot be compromised in a currency substrate.

Several factors, other than property values of the laminates, would have to be considered in determining the acceptability of a laminate as a currency substrate. These are:

1. Lamination of individual printed sheets would be cost prohibitive and the process would probably have to change over to roll printing and lamination.
2. Some method of sealing the edges of the cut laminate substrate is required.
3. The stacking of the plastic laminates may lead to problems in "blocking," (i.e., the inability of the plastic surfaces of the printed sheets to slide freely over one another) caused by a buildup of static electricity on the plastic surfaces. An "antistat" may be incorporated in the film itself or by a spray application of the antistat on the surfaces of the films at some stage. Conversely, some plastics may show excess slip characteristics, i.e., the opposite of sticking films.
4. The effect of the hot adhesive during lamination upon the print-stability of the printed sheet.
5. The esthetic qualities of the laminate would require evaluation for public acceptance.

II. Synthetic Papers and Plastic Films

For the synthetic papers tested in this program, it is not known whether the same dimensions now employed for the printed Federal Reserve notes would be adhered to in the strictest use especially in thickness (~ 115 μm). As shown in Tables 7 and 9, there is a great variance in the thickness among the synthetic papers and plastic films tested here. Only the Nomex-410-4 (#7) approaches the unprinted currency paper (#1a) in approximate thickness of the sheet. Most of the physical and mechanical properties of these materials will change as the thickness is varied. A good example of these changes that can occur within the same structural compositions, can be viewed by examination of the property changes based upon the different property values of the three Nomex samples 410-4 (#7); 410-5 (#8) and 414 (#9). The thicknesses of these three samples vary by up to 40 µm. The thicker Nomex 410-5 (139 µm) has better physical characteristics of cantilever stiffness, Elmendorf tear resistance and acceptable MIT fold endurance. Mechanically, Nomex-410-5 (#8) has better values for breaking strength, elongation to break, edge tear resistance and initial modulus. The main detriment of Nomex-410-5 (#8) as a currency paper substitute may be the fact that the Nomex papers will absorb approximately 1% water for each 10% rise in the relative humidity to reach a maximum value between 8-10% at equilibrium at 95% relative humidity(16). The rate of water absorption is highly dependent upon the thickness and density of the paper. The absorbed water would tend to cause the paper to swell slightly and this swelling may produce problems in handling in unconditioned automated devices. The hand or feel of the Nomexes are also relatively harsh.

Tyvek-1058 (#6) had the largest sheet thickness of all the samples tested in this program. Unflexed Tyvek-1058 suffers from low cantilever stiffness values and when flexed, these values fall well below the acceptable minimum of 88 µN•m in the direction of flex. Tyvek-1058 (#6) does have high values for Elmendorf tear resistance, MIT fold endurance, and elongation to break. However its breaking strength especially in the MD, and the initial modulus values are lower than any of the samples tested. On this basis, Tyvek-1058 (#6) would not be an acceptable currency paper substitute.

The unflexed Texoprint (#10) samples have high cantilever stiffness values in both MD and CD, but when flexed, considerable loss of stiffness occurs in the direction of flex. The Elmendorf and edge tear resistances of Texoprint paper are adequate but the low values for breaking strength (CD), elongation to break (MD) and initial modulus (CD), would eliminate this Texoprint paper as a currency substrate. The main rejection is due to the fact that Texoprint paper does not meet the minimum requirements for fold endurance in either MD or CD.

The Melinexes-377 (#10) and -442 (#11) were not designed for currency paper substitutes. Except for the weakness of Melinex-377 (#10) in the CD after flexing in CD, and the low Elmendorf tear resistance of Melinex-442 (#12), the Melinexes, in general, have good overall physical and mechanical properties for purposes other than currency substrate.

Again, only a few synthetic papers were investigated in this program. The single ply synthetic paper sheet would have advantages not inherent in a three ply laminate. The problems of delamination and edge-sealing of the laminates would be avoided. Although most of the synthetic papers are polymeric in structure, the texture of the synthetic surfaces is more akin to conventional paper than to plastic films, so that blocking tendencies would appear to be minimal. Still, abrasion, soil, ultraviolet light resistances, printability and the esthetic qualities of the synthetic paper selected as the currency paper substitute would have to be evaluated. The studies of these additional characteristics were not within the purview of this project.

Although differences were pointed out and comparisons were made among the currency papers, laminates, synthetic papers and plastic films, the comparisons were made mainly on a "points of interest" basis. Valid comparisons can only be made on materials which have at least the same nominal thicknesses.

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Appendix A

Figures 1 to 6

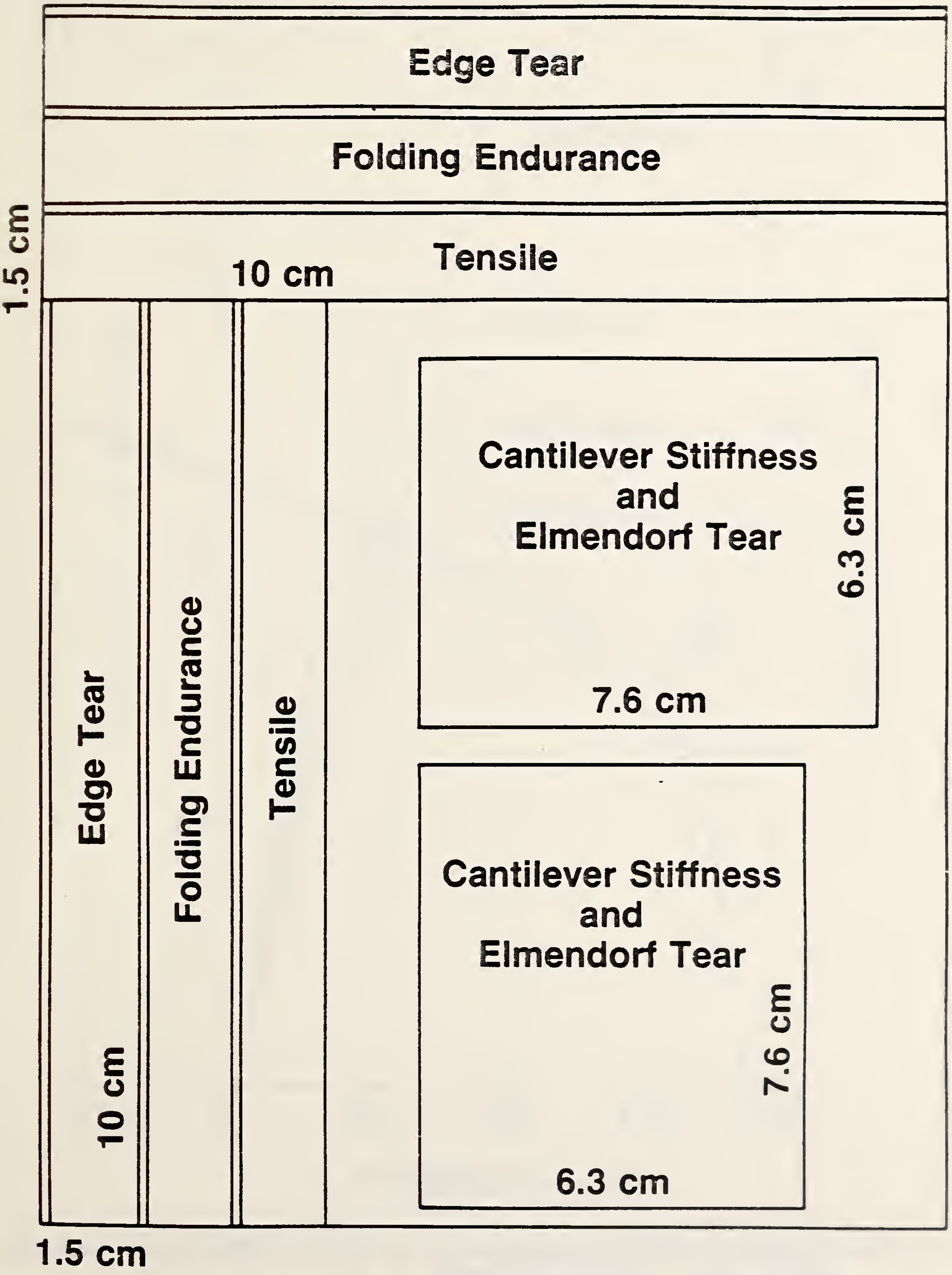

Fig. 1. Specimen Layout for Test Samples(6)

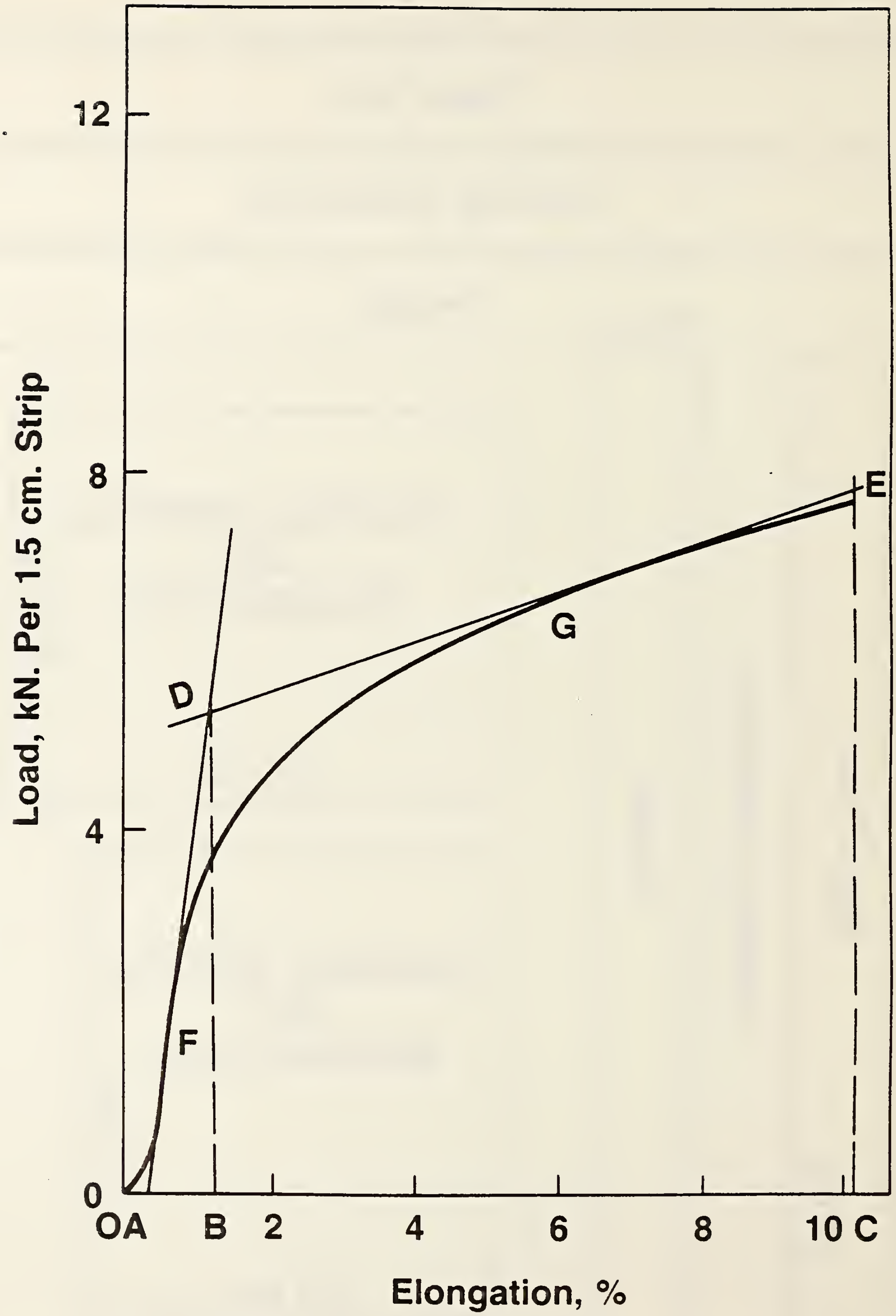

Fig. 2. Typical Load-Elongation Curve for Dry-Print Currency Paper, Cross Direction(6)

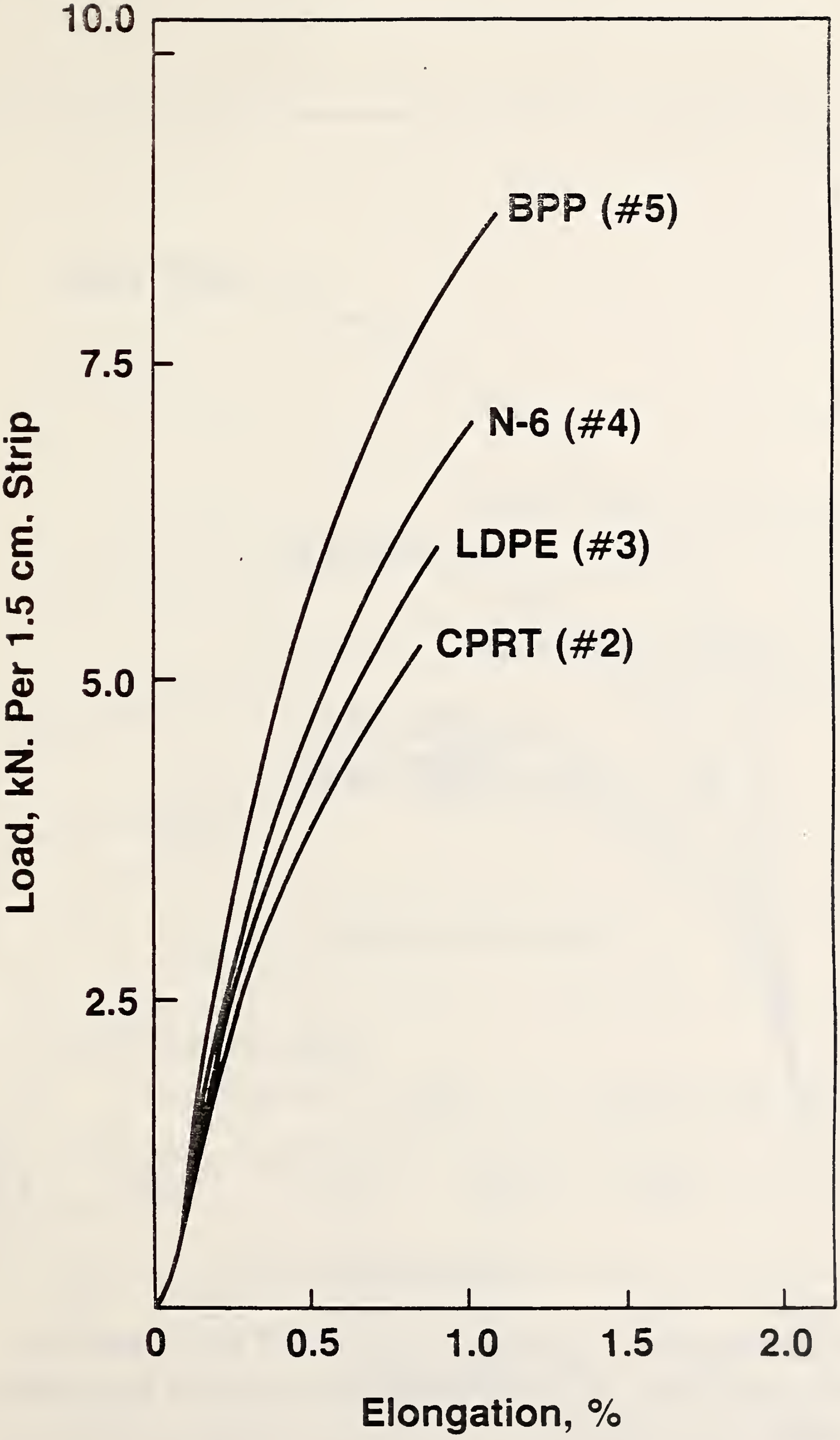

Fig. 3. Load-Elongation Curves for CPRT (#2) and Its Laminates (#3, 4, 5). Unflexed Control Samples, Machine Direction.

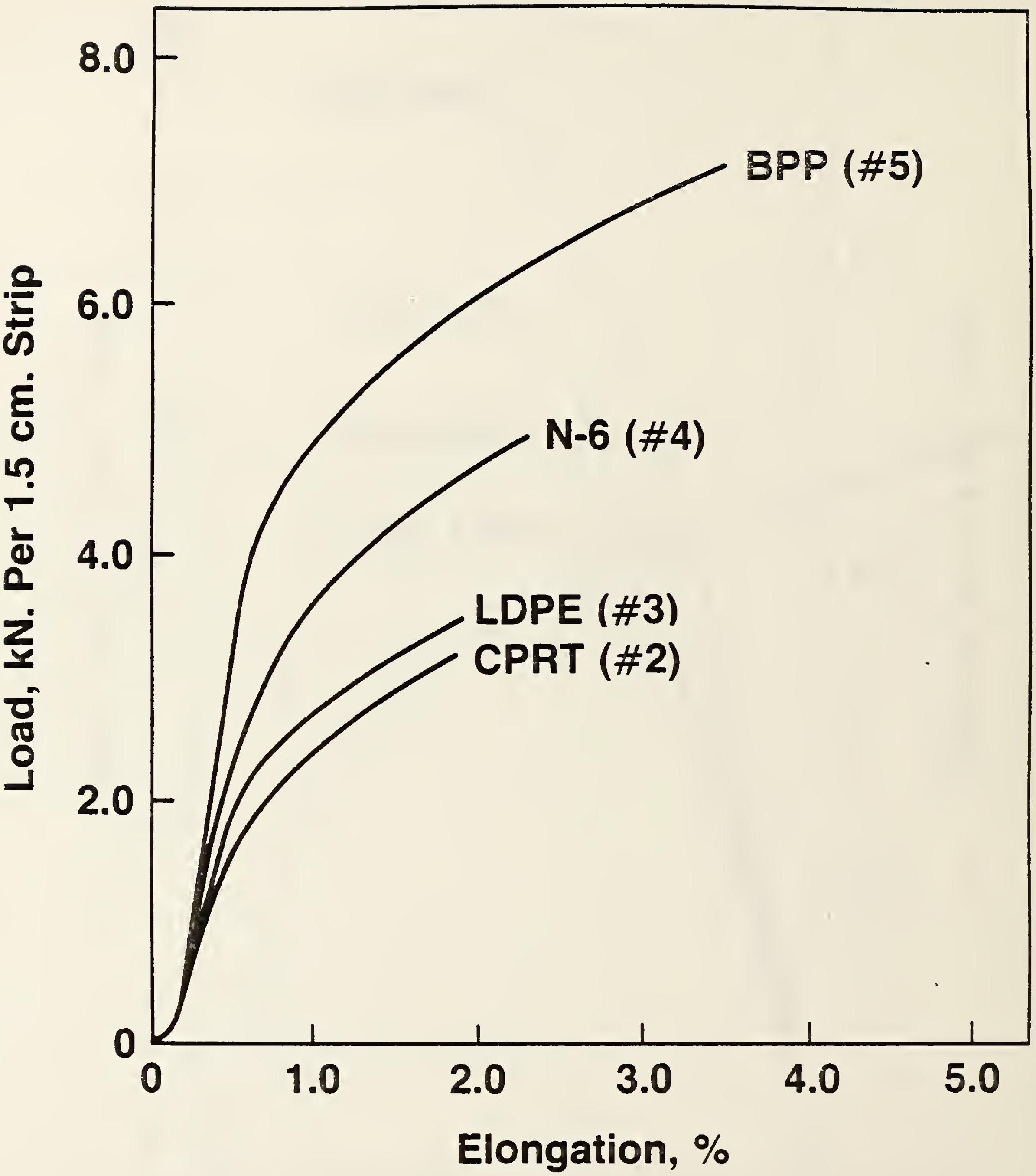

Fig. 4. Load-Elongation Curves for CPRT (#2) and Its Laminates (#3, 4, 5). Unflexed Control Samples, Cross Direction.

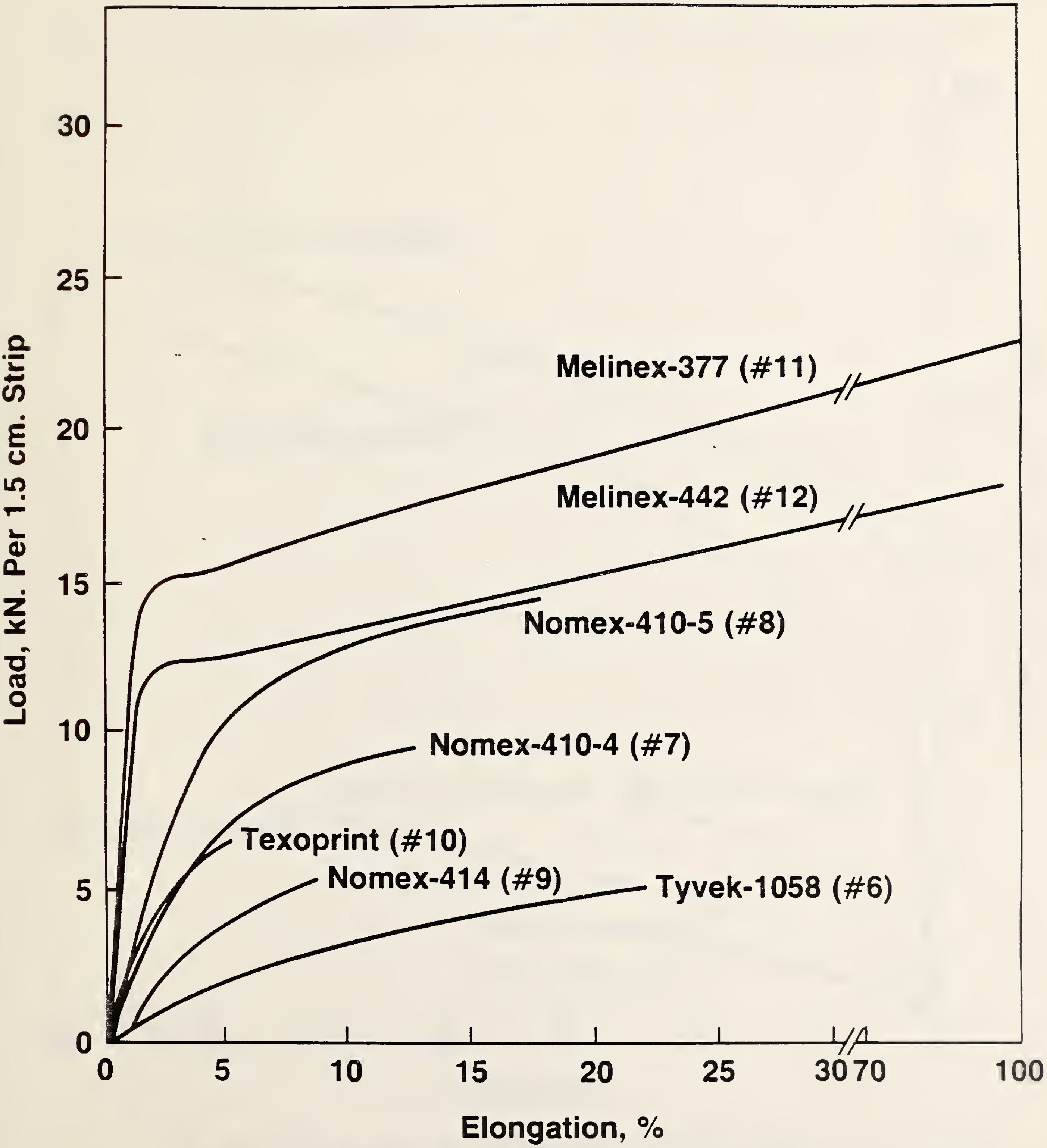

Fig. 5. Load Elongation Curves for Synthetic Polymeric Papers and Films. Unflexed Control Samples, Machine Direction.

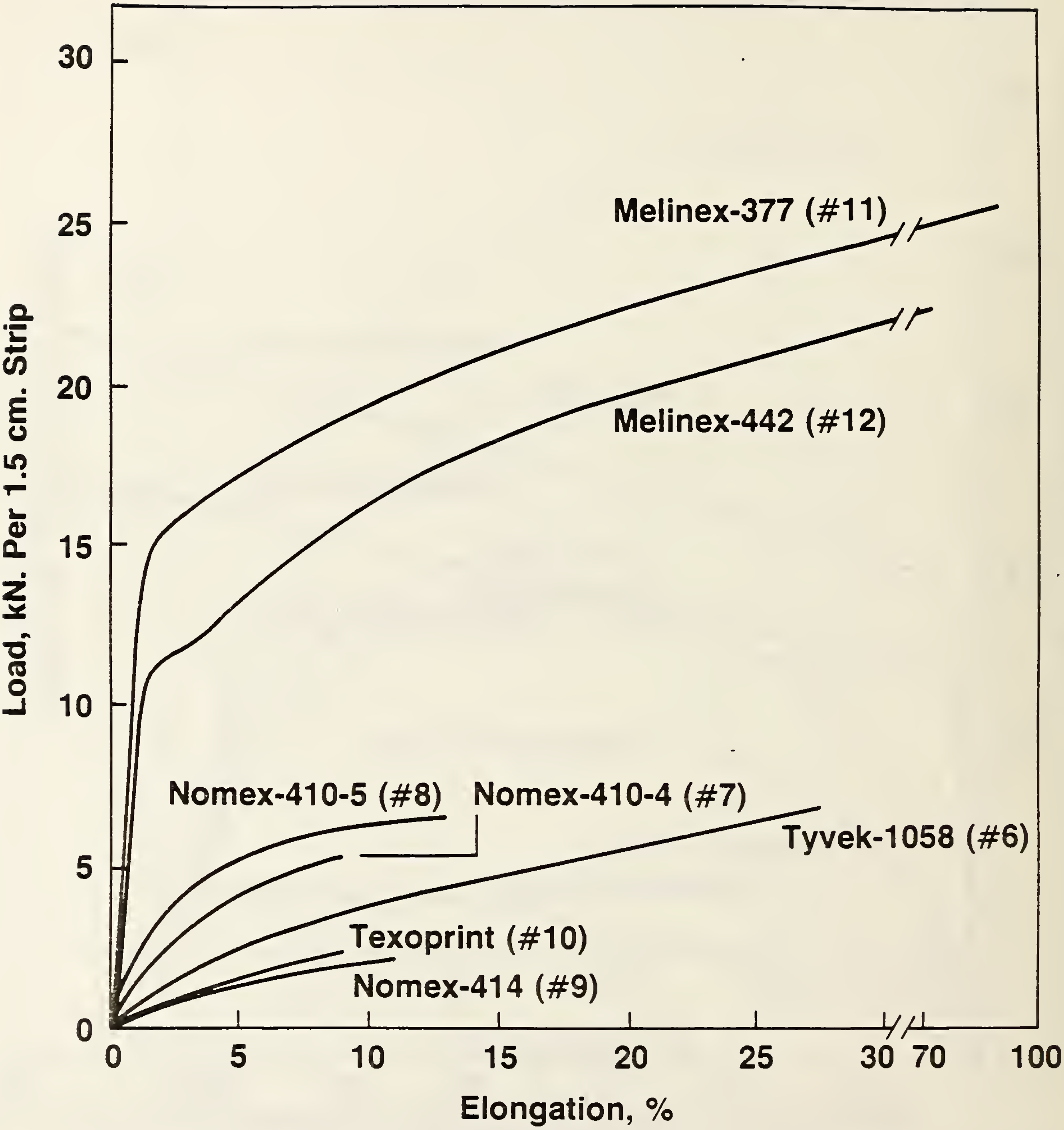

Fig. 6. Load Elongation Curves for Synthetic Polymeric Papers and Films. Unflexed Control Samples, Cross Direction.

Appendix B

Tables 1 to 10

Table 1

Plastic Films Acquired for Laminations

	Polymer	Project Polymer ID	Commercial Name or Designation[+]	Thickness µm	Film Coating	Supplier
1.	Cellophane	V-58C	250-V-58	20.3	PVDC[*]	OLIN
2.	" "	"	140-V-58	35.6	"	"
3.	K-Cellophane	KHB	KHB23	20.3	"	DuPont
4.	Cellulose Acetate	CA		25.4		Lustro Plastics
5.	" "	CA	398-3			Eastman Chemical
6.	Polyvinylidene dichloride	PVDC	Saran-18L	19.1	-	Dow Chemical
7.	" "	PVDC	Saran Wrap	12.7	-	" "
8.	Polyethylene-Low Density	LDPE	Wrap	12.7	-	Union Carbide
9.	Polyethylene-High Density	HDPE	Paxon	12.7	-	Allied Chemical
10.	Polyethylene Terephthalate	PET	Mylar, M24	12.7	PVDC	DuPont
11.	" "	"	" , M25	12.7, 17.8	"	"
12.	" "	"	Melinex 377, 442	102, 127	-	ICI America
13.	Polycaproamide	N-6	Nylon-6, 77C	15.2, 17.8, 25.4	-	Allied Chemical
14.	" "	"	" , 77K	" " "	PVDC	" "
15.	Polystyrene	PS	Trycite 1000	25.4, 38.1	-	Dow Chemical
			" 1100	25.4	-	" "
16.	Polypropylene	PP	Profax	30.5	-	Hercules
17.	BIAX-polypropylene	BPP	Bicor-PCS	17.8	PVDC	Mobil Chemical
18.	" "	BPP-1	Bicor-410LCM	19.1	-	" "
19.	" "	BPP-2	Bicor-OP5505	17.8	Copolymer PP	" "
20.	Polyvinyl Chloride	PVC	Krystaltite-T144	25.4	-	Allied Chemical
21.	Polyvinyl Fluoride	PVF	Tedlar	12.7	-	DuPont
22.	Ethylene-Tetrafluoroethylene Copolymer	E-TFE	Tefzel	12.7, 25.4	-	"
23.	Ethylene-Chlorotrifluoroethylene Copolymer	E-CTFE	Halar	25.4, 76.2, 127	-	Allied Chemical

[+] Commercial materials are identified to specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards.

[*] PVDC is #6 but lower molecular weight.

Table 2. List of Adhesives, Coatings and Other Agents Used for Laminations.

Commercial Name or Designation[+]	Type of Adhesive or Agent	Solvent	Heat Activation Temp., °C	Film Used[*]	Supplier
1. Adcote-102A	Two Component Cure	Toluene, Ketones	65-83	PP, PET, PVC, N-6	Morton Chemical
2. Adcote-503A	" "	" "	"	" "	" "
Catalyst F	Curing Agent	" "	>25	" "	" "
3. Adcote-636	Two Component Cure	Water-Isopropanol	65-87	KHB, PE, PET	" "
4. Airflex-410	Emulsion	Water	>25	CA, PET, PVC	Air Products, Inc.
5. Airflex-4500	Emulsion-Ter-Polymer Base	"	88	Paper, PE, N-6, PVDC	" " "
6. Duro-Lam-30-9075	Solution	Toluene	122	PET, PE, ECTFE, E-TFE	National Starch
7. Duro-Lam-30-9151	"	Ketones	108	Paper, PVC, PET	" "
8. Duro-Tak-72-9397	Emulsion	Water	122	" " ", PS	" "
9. Duro-Tak-80-1070	Pressure Sensitive	Organic Mixture	>25	PVC	" "
10. Numel-502	Hot Melt	-	205	PE, PP	Gulf Oil Co.
11. Numel-610	" "	-	177	" "	" " "
12. Polycoat-CP30P	Chlorinated PP	Toluene	93	PP, PE	East Coast Chemical Company
13. Polycoat-CP32P	" "	"	89	Ink Binder PP	" " " Co.
14. Polycoat-CP26P-25S	" "	"	80	PP, PE	" " " "
15. A1410B	Two Component Cure	Ketones	70-85	Paper, PET, PE, PVF	B. F. Goodrich
A1411B	Catalyst	"	>25	--	" "
16. A1412B	Pressure Sensitive	Toluene	>25	PE, PET, PP, PVC, PVF	" "
17. A1450B	" "	Toluene, Ketones	>25	" " " " "	" "
18. Kenamines	Antistats	Amines	-	General Purpose	Witco, Humko Div.
19. Kodaflex-DEP	Plasticizer	Diethylphthalate	-	" "	Eastman Chemical
20. Kodaflex-DMP	"	Dimethylphthalate	-	" "	" "

[+] Cf, Table 1 for disclaimer.
[*] Cf, Table 1 for Polymer ID.

Table 3. Laminations[a] of Currency Paper (CPRT) With Plastic Films

Film-CPRT Laminates[b,c]	Film Thickness μm	Number of Samples	Paper Direction	Temp.[d] °C	Pressure[e] MPa	Visual Appearance		Manual Flex De-lamination
						Seals	Blisters	
1. Biax-poly-propylene (BPP)	17.8	15	MD	146	1.17	Good	None	No
		15	CD	"	"	"	"	"
2. " " (BPP)[f]	17.8	5	MD	"	"	"	"	"
		6	CD	"	"	"	"	"
3. Polycapro-amide (N-6)	15.2	15	MD	146	1.17	Good	None	No
		15	CD	"	"	"	"	"
4. " (N-6)[f]	15.2	5	MD	"	1.17	Good	None	No
		6	CD	"	"	"	"	"
5. Polyethylene, Low Density (LDPE)	12.7	15	MD	142	1.17	Good	None	No
		15	CD	"	"	"	"	"

a. All samples compression laminated.
b. These laminates used for property determinations.
c. Sample size, 15 x 30 (CD) or 28 cm^2 (MD).
d. Pre-heat time, 4.0 minutes.
e. Press time, 1.0 minute.
f. Sent to BEP for evaluation.

Table 4. Preparations of Test Laminates From CPRT and Various Plastic Films by Compression Molding Techniques.

Film-CPRT Laminates[a]	Film Thickness µm	Paper Direction	Press Temp.[b] °C	Average Pressure[c] MPa	Visual Appearance Seals	Visual Appearance Blisters	Manual Flex De-lamination
1. Biax-polypropylene (BPP)[d]	17.8	CD	146	1.17	Good	None	Yes (PE from paper)
2. " " (BPP)[e]	17.8	CD	132	1.35	Good	None	No
3. Polycaproamide (N-6)[f,g]	15.2	MD	148	1.15	Good	None	No
4. Polyethylene terephthalate (PET)[f,g]	15.2	CD	148	1.35	Good	None	Some edges
5. " (PET)[f,h]	12.7	MD	148	1.60	Good	None	No
6. Ethylene-chlorotrifluoroethylene Copolymer (E-CTFE)[i]	25.4	MD	146	1.17	Fair	Yes	Yes
7. " (E-CTFE)[i]	25.4	CD	146	1.17	Fair	Yes	Yes
8. Polyvinyl Chloride (PVC)[h]	25.4	CD	146	1.60	Good	None	No
9. Polyvinyl Fluoride (PVF)[g]	12.7	MD	146	1.17	Good	None	No
10. Polyvinylidene Chloride[e]	12.7	CD	138	1.60	Good	None	Some edges

a. All laminate 15 x 30 cm^2.
b. Plate pre-heat time, 4.0 minutes.
c. Press time, 1.0 minute.
d. CPRT coated with PE.
e. CPRT coated with chlorinated PP adhesive, 11% solids.
f. Film coated with PVDC.
g. CPRT coated with vinyl-acetate-ethylene (VAE) adhesive, 11% solids.
h. CPRT coated with aqueous VAE adhesive, 55% solids.
i. CPRT coated with Duro-lam adhesive.

Table 5. Preparations of Test Samples by Roll Laminations.

Film-CPRT Laminates	Film Thickness µm	Paper Direction	Lamination Temp. °C	Roll Pressure MPa[a]	Nip Opening cm	Surface Speed cm/min	Visual Appearance		Manual Flex De-laminati
							Seals	Blisters	
1. Polyvinyl Chloride (PVC)[b]	25.4	MD	103	0.48	0.018	152	Good	None	No
2. Ethylene-chloro-Trifluoro-ethylene Copolymer (E-CTFE)[c]	25.4	MD	130	0.55	0.058	152	Good	None	No
3. " (E-CTFE)[c]	25.4	CD	130	0.55	0.058	152	Good	None	No
4. Ethylene-tetra fluoroethylene Copolymer (E-TFE)[c]	12.7	MD	130	0.55	0.058	305	Good	None	No
5. " (ETFE)[c]	25.4	MD	130	0.55	0.058	305	Good	None	No
6. Tyvek-1058[d]	14.5[e]	CD	114	0.55	0.018	305	Good	None	No
7. "	11.5[e]	CD	114	0.55	0.018	305	Good	None	No
8. "	18.0[e]	MD	114	0.55	0.018	305	Good	None	No
9. CPRT[d]	20.0[e]	MD	108	0.55	0.018	152	Good	None	No
10. "	13.5[e]	MD	108	0.55	0.018	152	Good	None	No

a. Numbers indicate pressure on rolls.
b. CPRT coated with solution of Vinylacetate-ethylene (VAE) in methyl ethyl ketone, 11% solids.
c. CPRT coated with Duro-lam adhesive.
d. Coated with AF-4500, 55% solids; coating roll sealed at temperature indicated.
e. Average thickness/side of applied coating.

Table 6. Some Physical Properties of Test Laminates Prepared From CPRT and Various Plastic Films After Flexing.

Samples	Cantilever Stiffness µN·m		Elmendorf Tear Resistance mN		Thickness		Flex Direction		
	MD	CD	MD	CD	µm	mils.	MD	CD	Unflexed
A. Compression Molded									
1. BPP (2)[a]	-	-	764	622	121.6	4.8		x	
2. N-6 (3)	-	-	902	981	114.3	4.5	x		
3. PET (4)	-	-	1177	862	111.4	4.4		x	
4. PET (5)	-	-	1706	1118	133.4	5.3	x		
5. PVC (8)	353.9	294.1	1098	1176	152.4	6.0	x		
6. PVF (9)	281.4	196.1	814	794	106.7	4.2	x		
7. PVDC (10)	-	-	529	627	111.8	4.4		x	
B. Roll Laminated or Coated									
1. PVC (1)[b]	723.5	656.9	1961	1961	195.6	7.7		x	
2. E-CTFE (2)	453.9	360.0	2393	3295	157.5	6.2			x
3. E-TFE (4)	198.1	202.9	4864	12552	152.4	6.0	x		
4. E-TFE (5)	426.5	339.2	>15690		185.4	7.3	x		
5. Tyvek-1058 (6)	112.8	89.0	3138	3452	202.4	7.9		x	
6. Tyvek-1058 (7)	167.7	200.0	2981	4864	190.8	7.5		x	
7. Tyvek-1058 (8)	86.3	115.0	3922	2510	204.7	8.1	x		
8. CPRT (9)	126.5	68.6	785	785	132.8	5.2	x		
9. CPRT (10)	125.5	57.8	785	785	119.4	4.7	x		

a. Numbers in parentheses refer to samples prepared in Table 4.
b. Numbers in parentheses refer to samples prepared in Table 5.

Table 7. Physical Properties of Currency Papers, Laminates and Synthetic Papers Flexed in the MD

	Cantilever Stiffness µN·m								Elmendorf Tear mN							
	Unflexed				Flexed				Unflexed				Flexed			
	MD	S*	CD	S	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S
1. a) UCP-unprinted	451.1	49.0	196.1	19.6	264.8	19.6			971	20	1,000	20	981	69		
b) PCP-printed	304.0		156.9		225.5				902		833		843			
2. CPRT	124.5	6.9	63.7	4.9	103.0	9.8	65.7	3.9	529	69	569	39	510	88	510	49
3. CPRT/LDPE	142.2	14.7	85.3	18.6	137.3	16.7	75.5	5.9	588	69	598	39	657	69	608	69
4. CPRT/N-6	179.4	10.8	120.6	5.9	160.8	9.8	115.7	5.9	1,010	98	1,069	147	902	59	1,108	49
5. CPRT/BPP	309.9	36.3	238.2	27.4	274.6	28.4	265.7	10.8	578	39	627	49	578	39	588	69
6. Tyvek-1058	152.0	35.3	145.1	26.5	48.0	7.8	143.2	23.5	5,854	990	3,746	1,000	5,442	1,000	5,001	1,157
7. Nomex-410-4	215.7	13.7	172.6	7.8	200.0	17.6	157.9	17.6	2,098	343	3,000	304	1,726	196	2,726	278
8. Nomex-410-5	480.5	48.0	265.7	13.7	445.2	41.2	217.7	11.8	2,157	186	5,143	637	2,108	157	5,207	853
9. Nomex-414	122.6	8.8	42.2	4.9	81.4	5.9	30.4	3.9	2,059	255	4,275	314	1,932	88	3,707	618
10. Texoprint	894.3	113.7	435.4	57.8	206.9	21.6	254.9	58.8	981	49	1,069	147	912	98	912	78
11. Melinex-377	740.3	44.1	796.2	30.4	715.8	43.1	774.7	41.2	1,657	59	1,559	29	1,667	98	1,618	69
12. Melinex-442	365.8	11.8	424.6	14.7	363.8	13.7	438.3	13.7	461	49	510	78	451	88	480	29

*S means standard deviation.

Table 7 - continued (MD Flex)

	MIT Fold Endurance[a], 1000 g Double Folds								Thickness µm							
	Unflexed				Flexed				Unflexed				Flexed			
	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S	MD	S	CS	S
1. a) UCP-unprinted	4.0		4.29		5.0				123.0	2.0	123.0	2.0	123.0	2.0	123.0	2.0
b) PCP-printed																
2. CPRT	21.6	$4.6^{(3)b}$	14.6	$5.8^{(3)}$	8.8	$3.4^{(8)}$	7.0	$0.6^{(7)}$	92.0	3.4	91.9	2.4	84.3	2.4	83.1	2.1
3. CPRT/LDPE	15.3	$2.5^{(3)}$	15.9	$6.1^{(3)}$	11.4	$2.9^{(3)}$	15.5	$1.8^{(3)}$	90.2	2.2	90.9	2.1	92.5	2.2	90.4	1.7
4. CPRT/N-6	47.7	$4.8^{(3)}$	37.4	$5.9^{(3)}$	43.8	$1.5^{(3)}$	30.8	$6.9^{(3)}$	115.3	3.4	123.7	3.9	110.0	1.9	104.4	2.7
5. CPRT/BPP	>75.0		>75.0		>75.0		>80.0		113.3	3.4	113.3	3.1	114.5	3.0	110.5	2.9
6. Tyvek-1058	>50.0		>50.0		>50.0		>50.0		168.9	7.6	168.9	16.8	168.4	14.0	171.2	12.2
7. Nomex-410-4	5.8	0.7	7.5	1.0	6.2	1.0	7.1	1.3	119.9	3.8	119.4	3.8	119.6	4.8	122.9	4.8
8. Nomex-410-5	5.7	0.9	8.8	2.0	6.3	1.1	9.0	1.6	139.2	3.0	139.2	2.5	140.2	2.5	140.2	2.3
9. Nomex-414	7.8	2.9	4.4	1.0	9.9	1.9	4.4	0.8	100.1	2.0	98.8	3.0	99.8	1.8	98.5	5.6
10. Texoprint	1.4	0.5	1.1	0.5	1.3	0.4	1.0	0.2	154.2	2.5	152.4	2.3	159.5	3.8	160.0	3.3
11. Melinex-377	50.4	$1.0^{(3)}$	84.0	$7.9^{(3)}$	58.5	$3.3^{(3)}$	71.2	$12.1^{(3)}$	139.9	2.0	137.7	2.0	135.9	2.8	136.6	2.5
12. Melinex-442	29.9	$3.5^{(3)}$	79.5	$7.6^{(3)}$	36.6	$2.0^{(3)}$	84.5	$15.8^{(3)}$	103.1	1.8	102.6	1.8	102.1	1.3	101.3	1.3

a. All values x 10^3.

b. Superscript numbers refer to samples in average.

Table 8. Mechanical Properties of Currency Papers, Laminates and Synthetic Papers Flexed in the MD

	Breaking Strength kN/m								Elongation to Break %							
	Unflexed				Flexed				Unflexed				Flexed			
	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S
1. a) UCP-unprinted	7.6	0.5	4.1	0.2	7.2	0.8			3.4	0.3	4.6	0.8	3.4	0.5		
b) PCP-printed	8.4		4.1		8.0				3.6		6.9		3.5			
2. CPRT	5.4	0.3	3.1	0.2	5.7	0.3	3.1	0.2	0.8	0.1	1.8	0.3	0.8	0.0	1.7	0.2
3. CPRT/LDPE	6.0	0.4	3.5	0.1	6.2	0.3	3.5	0.1	0.9	0.1	1.8	0.4	0.9	0.1	1.8	0.2
4. CPRT/N-6	7.2	0.3	4.7	0.1	6.7	0.3	4.8	0.1	0.9	0.1	2.3	0.3	1.0	0.0	2.0	0.3
5. CPRT/BPP	8.4	0.7	7.0	1.2	7.3	0.4	8.0	0.3	1.1	0.1	3.5	0.8	1.0	0.1	3.3	0.5
6. Tyvek-1058	4.4	0.6	6.0	0.8	4.3	0.6	6.0	0.7	23.0	3.4	27.5	2.4	22.5	3.8	26.6	1.5
7. Nomex-410-4	9.8	0.5	5.4	0.2	8.7	0.5	5.3	0.3	11.9	1.5	8.8	1.8	9.5	2.1	9.9	1.4
8. Nomex-410-5	14.3	0.6	6.3	0.6	13.2	0.5	6.2	0.3	18.3	1.3	13.7	1.2	14.4	2.5	13.1	2.5
9. Nomex-414	5.2	0.5	2.4	0.2	4.9	0.4	2.2	0.1	7.1	1.3	11.3	1.2	6.9	1.2	10.1	1.3
10. Texoprint	5.6	0.9	2.6	0.3	5.1	0.5	2.3	0.2	2.9	0.1	8.8	0.4	3.3	0.2	9.0	0.2
11. Melinex-377	21.9	0.7	23.1	0.8	21.4	0.8	23.0	0.7	105.1	7.9	91.4	7.5	100.0	7.4	91.0	7.0
12. Melinex-442	16.8	0.6	19.8	1.1	15.5	0.9	20.3	0.7	94.6	7.7	71.0	7.5	76.9	13.0	73.4	8.1

Table 8 - continued (MD Flex)

	Energy to Break J/M^2								Initial Modulus GN/m^2							
	Unflexed				Flexed				Unflexed				Flexed			
	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S
1. a) UCP-unprinted	153.0	19.6	193.5	32.7	160.2	19.6										
b) PCP-printed	200.0		228.8		183.0				6.1		2.8		6.4			
2. CPRT	26.2	2.6	37.3	5.2	28.3	2.3	34.5	5.6	21.5	1.5	8.9	1.0	18.2	1.2	9.8	1.4
3. CPRT/LDPE	34.3	5.7	39.8	7.8	35.9	2.9	44.1	5.6	23.6	1.7	10.2	0.9	23.1	1.7	10.0	1.1
4. CPRT/N-6	43.2	4.6	75.8	8.5	39.7	2.9	67.3	9.8	19.1	1.2	9.1	0.8	15.7	1.3	10.2	0.8
5. CPRT/BPP	59.5	11.0	212.2	57.3	44.1	4.1	181.9	37.4	21.8	1.9	11.4	1.3	16.1	0.7	12.7	0.7
6. Tyvek-1058	642.0	165.4	972.7	176.5	598.8	160.2	943.3	154.9	0.4	0.0	0.5	0.0	0.2	0.0	0.5	0.1
7. Nomex-410-4	896.9	164.7	366.7	93.5	587.0	145.1	415.8	73.2	3.5	0.5	2.4	0.1	2.9	0.2	2.2	0.1
8. Nomex-410-5	1996.0	210.5	690.0	85.6	1446.0	309.0	647.2	143.8	3.8	0.1	2.4	0.1	3.6	0.1	2.2	0.1
9. Nomex-414	273.9	80.4	183.0	39.2	245.1	64.7	143.2	23.5	2.5	0.1	0.8	0.09	2.0	0.1	0.6	0.0
10. Texoprint	113.7	20.9	161.5	13.7	102.0	15.0	143.8	9.8	3.8	0.5	1.4	0.2	1.4	0.1	0.9	0.1
11. Melinex-377	758.3[a]	431.5	605.4[a]	307.2	733.5[a]	418.4	607.3[a]	346.5	3.9	0.3	4.1	0.3	3.7	0.2	3.7	0.3
12. Melinex-442	728.9[a]	438.0	476.6[a]	424.9	536.7[a]	836.8	426.9[a]	320.3	3.9	0.3	4.4	0.3	4.1	0.3	4.5	0.2

a. Melinex values x 10

Table 8 - continued (MD Flex)

	Edge Tear kN/m								Energy to Edge Tear J/m^2							
	Unflexed				Flexed				Unflexed				Flexed			
	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S
1. a) UCP-unprinted																
b) PCP-printed																
2. CPRT	0.3	0.1	0.6	0.2	0.3	0.0	0.4	0.1	0.3	0.1	1.4	0.9	0.4	0.1	0.8	0.6
3. CPRT/LDPE	0.4	0.1	0.5	0.1	0.4	0.1	0.8	0.2	0.5	0.1	1.1	0.4	0.5	0.1	2.0	1.0
4. CPRT/N-6	0.6	0.1	1.0	0.2	0.6	0.1	1.0	0.2	1.0	0.4	3.0	1.0	1.2	0.9	3.3	1.4
5. CPRT/BPP	1.7	0.4	1.8	0.4	1.1	0.1	2.2	0.5	5.4	2.2	8.4	2.8	2.2	0.7	8.5	2.9
6. Tyvek-1058	1.1	0.2	1.1	0.2	1.0	0.2	0.6	0.2	26.9	7.8	25.4	5.9	24.3	7.7	11.1	5.0
7. Nomex-410-4	0.8	0.2	0.8	0.2	0.9	0.1	1.1	0.3	6.0	1.2	6.1	2.0	6.2	1.2	10.2	3.4
8. Nomex-410-5	1.0	0.2	1.1	0.1	0.9	0.1	0.9	0.1	8.4	2.6	10.7	2.1	7.2	1.7	8.2	2.4
9. Nomex-414	0.9	0.2	1.0	0.2	0.8	0.1	1.1	0.2	6.5	2.6	20.3	7.5	6.2	1.4	25.9	10.6
10. Texoprint	1.1	0.2	1.4	0.2	0.9	0.2	1.4	0.2	11.2	3.9	36.7	8.8	9.3	2.3	48.2	10.0
11. Melinex-377	0.8	0.1	0.9	0.16	1.0	0.1	0.8	0.2	87.6	37.3	69.3	26.1	58.2	12.4	49.7	21.6
12. Melinex-442	1.4	0.2	1.1	0.2	1.6	0.2	1.3	0.3	60.8	18.9	45.1	13.7	43.1	11.1	39.2	7.8

Table 9. Physical Properties of Currency Papers, Laminates and Synthetic Papers Flexed in the CD

	Cantilever Stiffness μN·m								Elmendorf Tear mN							
	Unflexed				Flexed				Unflexed				Flexed			
	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S
1. a) UCP-unprinted	451.1	49.0	196.1	19.6			137.3	9.8	971	20	1,000	20			961	20
b) PCP-printed	304.0		156.9				117.7		902		833				853	
2. CPRT	124.5	6.9	63.7	4.9	123.5	8.8	58.8	2.9	529	69	569	39	510	39	529	59
3. CPRT/LDPE	142.2	14.7	85.3	18.6	143.2	9.8	69.6	4.9	588	69	598	39	608	59	677	88
4. CPRT/N-6	179.4	10.8	120.6	5.9	185.3	6.9	119.6	8.8	1,010	98	1,069	147	1,069	59	931	49
5. CPRT/BPP	309.9	36.3	238.3	27.4	327.5	23.5	191.2	7.8	578	39	627	49	559	29	602	39
6. Tyvek-1058	152.0	35.3	145.1	26.5	105.9	7.8	49.0	7.8	5,854	990	3,746	1,000	5,903	1,373	4,569	931
7. Nomex-410-4	215.7	13.7	172.6	7.8	205.9	18.6	125.5	9.8	2,098	343	3,001	304	1,618	235	3,471	147
8. Nomex-410-5	480.5	48.0	265.7	13.7	467.7	28.4	176.5	7.8	2,157	186	5,138	637	1,843	108	6,119	863
9. Nomex-414	122.6	8.8	42.2	4.9	117.7	11.8	25.5	2.9	2,059	255	4,275	314	2,020	88	3,795	422
10. Texoprint	894.3	113.7	435.4	57.8	638.4	112.8	119.6	6.9	981	49	1,069	147	853	69	971	157
11. Melinex-377	740.3	44.1	796.2	30.4	747.2	25.5	762.9	25.5	1,657	59	1,559	29	1,618	39	1,647	59
12. Melinex-442	365.8	11.8	424.6	14.7	361.8	11.8	417.7	11.8	461	49	510	78	539	118	500	39

Table 9 - continued (CD Flex)

	MIT Fold Endurance[a], 1000 g Double Folds								Thickness µm							
	Unflexed				Flexed				Unflexed				Flexed			
	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S
1. a) UCP-unprinted	4.0		4.29				3.9		123.0	2.0	123.0	2.0	123.0	2.0	123.0	2.0
b) PCP-printed																
2. CPRT	21.6	$4.6^{(3)b}$	14.6	$5.8^{(3)}$	11.0	$3.2^{(8)}$	8.2	$3.9^{(8)}$	92.0	3.4	91.9	2.4	84.6	1.9	83.8	2.4
3. CPRT/LDPE	15.3	$2.5^{(3)}$	15.9	$6.1^{(3)}$	17.7	$2.1^{(3)}$	13.9	$2.9^{(3)}$	90.2	2.2	90.9	2.1	89.9	2.1	93.2	3.1
4. CPRT/N-6	47.7	$4.8^{(3)}$	37.4	$5.9^{(3)}$	39.4	$9.3^{(3)}$	47.3	$8.8^{(5)}$	115.3	3.4	123.7	3.9	105.4	1.8	110.7	3.0
5. CPRT/BPP	>75.0		>75.0		>75.0		>75.0		113.3	3.4	113.3	3.1	109.2	3.1	110.5	3.7
6. Tyvek-1058	>50.0		>50.0		>50.0		>50.0		168.9	7.6	168.9	16.8	163.8	5.6	167.1	16.0
7. Nomex-410-4	5.8	0.7	7.4	1.0	6.6	1.1	7.0	1.3	119.9	3.8	119.4	3.8	122.4	5.3	119.1	2.3
8. Nomex-410-5	5.7	0.9	8.8	2.0	6.1	1.5	8.1	0.9	139.2	3.0	139.7	2.5	138.9	1.5	137.9	2.3
9. Nomex-414	7.8	2.9	4.4	1.0	10.0	1.3	4.5	0.6	100.1	2.0	98.8	3.0	97.5	1.8	99.3	2.0
10. Texoprint	1.4	0.5	1.1	0.5	1.6	0.5	1.1	0.6	154.2	2.5	152.4	2.3	154.4	2.5	154.4	2.8
11. Melinex-377	50.5	$1.1^{(3)}$	84.0	$7.9^{(3)}$	59.9	$7.8^{(3)}$	75.9	$9.2^{(3)}$	136.9	2.0	137.7	2.0	134.9	1.3	135.4	1.8
12. Melinex-442	29.9	$3.4^{(3)}$	79.5	$7.6^{(3)}$	39.1	$4.8^{(3)}$	71.5	$12.5^{(3)}$	103.1	1.8	102.6	1.8	101.6	0.8	101.1	0.8

a. All values x 10^3.

b. Superscript numbers refer to samples in average.

Table 10. Mechanical Properties of Currency Papers, Laminates and Synthetic Papers Flexed in the CD

		Breaking Strength kN/m								Elongation to Break %							
		Unflexed				Flexed				Unflexed				Flexed			
		MD	S	CD	S	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S
1.	a) UCP-unprinted	7.6	0.5	4.1	0.2			3.9	0.3	3.4	0.3	4.6	0.8			4.3	0.4
	b) PCP-printed	8.4		4.1				4.0		3.6		6.9				6.7	
2.	CPRT	5.4	0.3	3.1	0.2	5.6	0.3	3.1	0.1	0.8	0.1	1.8	0.3	0.8	0.0	1.6	0.3
3.	CPRT/LDPE	6.0	0.4	3.5	0.1	6.0	0.3	3.4	0.1	0.9	0.1	1.8	0.4	0.9	0.1	1.9	0.4
4.	CPRT/N-6	7.2	0.3	4.7	0.1	7.2	0.2	4.4	0.3	0.9	0.1	2.3	0.3	1.0	0.0	1.9	0.3
5.	CPRT/BPP	8.4	0.7	7.0	1.2	8.9	0.5	5.6	0.1	1.1	0.0	3.5	0.8	1.1	0.1	2.6	0.3
6.	Tyvek-1058	4.4	0.6	6.0	0.8	4.6	0.5	6.2	0.8	23.0	3.4	27.5	2.4	24.5	1.3	28.7	3.3
7.	Nomex-410-4	9.8	0.5	5.4	0.2	8.9	0.4	5.2	0.2	11.9	1.5	8.8	1.8	10.4	1.6	8.8	1.7
8.	Nomex-410-5	14.3	0.6	6.3	0.6	14.1	0.4	6.3	0.2	18.3	1.3	13.7	1.2	17.3	1.2	13.8	1.7
9.	Nomex-414	5.2	0.5	2.4	0.2	4.9	0.4	2.3	0.2	7.1	1.3	11.3	1.2	6.6	1.1	11.3	1.1
10.	Texoprint	5.6	0.9	2.6	0.3	5.3	0.9	2.6	0.4	2.9	0.1	8.8	0.4	3.1	0.2	8.4	0.4
11.	Melinex-377	21.9	0.7	23.1	0.8	21.5	0.7	---	---	105.1	7.9	91.4	7.5	99.6	6.4	---	---
12.	Melinex-442	16.8	0.6	19.8	1.1	16.9	0.6	18.5	1.0	94.6	7.7	71.0	7.5	96.9	8.2	58.2	12.3

Table 10 - continued (CD Flex)

	Edge Tear kN/m								Energy to Edge Tear J/m^2							
	Unflexed				Flexed				Unflexed				Flexed			
	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S
1. a) UCP-unprinted																
b) PCP-printed																
2. CPRT	0.3	0.1	0.6	0.2	0.3	0.1	0.4	0.1	0.3	0.1	1.4	0.9	0.3	0.0	0.7	0.2
3. CPRT/LDPE	0.4	0.1	0.5	0.1	0.4	0.1	0.8	0.2	0.5	0.1	1.1	0.4	0.5	0.1	2.2	0.9
4. CPRT/N-6	0.6	0.1	1.0	0.2	0.5	0.1	1.0	0.2	1.0	0.4	3.0	1.0	1.0	0.6	3.6	1.4
5. CPRT/BPP	1.7	0.4	1.8	0.4	1.8	0.2	1.8	0.3	5.4	2.2	8.4	2.8	4.8	1.3	5.8	1.4
6. Tyvek-1058	1.1	0.2	1.1	0.2	0.6	0.1	0.6	0.2	26.9	7.8	25.4	5.9	9.3	1.8	10.3	3.6
7. Nomex-410-4	0.8	0.2	0.8	0.2	0.9	0.2	0.8	0.2	6.0	1.2	6.1	2.0	5.8	1.7	6.7	2.3
8. Nomex-410-5	1.0	0.2	1.1	0.1	0.90	0.2	1.1	0.2	8.4	2.6	10.7	2.1	6.7	1.4	12.5	3.3
9. Nomex-414	0.9	0.2	1.0	0.1	1.2	0.1	1.1	0.1	6.5	2.6	20.3	7.5	11.37	1.8	20.1	5.9
10. Texoprint	1.1	0.2	1.4	0.2	1.2	0.3	1.4	0.2	11.2	3.9	36.7	8.8	14.7	5.9	41.3	8.4
11. Melinex-377	0.8	0.1	0.9	0.2	0.6	0.1	0.7	0.1	87.6	37.3	69.3	26.1	45.1	6.5	39.9	8.5
12. Melinex-442	1.4	0.2	1.1	0.2	1.2	0.2	1.1	0.1	60.8	18.9	45.1	13.7	44.4	7.8	37.3	8.5

Table 10 - continued (CD Flex)

	Energy to Break J/M^2								Initial Modulus GN/m^2							
	Unflexed				Flexed				Unflexed				Flexed			
	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S	MD	S	CD	S
1. a) UCP-unprinted	153.0	19.6	193.5	32.7			219.6	26.1								
b) PCP-printed	200.0		228.8				228.8		6.1		2.8				2.3	
2. CPRT	26.2	2.6	37.3	5.2	28.8	2.6	33.3	5.9	21.5	1.5	8.9	1.0	22.8	1.8	8.1	0.7
3. CPRT/LDPE	34.3	5.7	39.8	7.8	32.7	3.3	45.8	7.2	23.6	1.7	10.2	0.9	23.6	1.4	9.5	1.1
4. CPRT/N-6	43.2	4.6	75.8	8.5	45.6	2.5	57.7	11.3	19.1	1.2	9.1	0.8	19.8	1.5	7.9	0.9
5. CPRT/BPP	59.5	11.0	212.2	57.3	64.2	6.1	103.0	10.4	21.8	1.9	11.4	1.3	21.3	0.8	10.5	1.5
6. Tyvek-1058	642.0	165.4	972.7	176.5	678.6	96.1	1,024.4	211.8	0.4	0.0	0.5	0.0	0.4	0.0	0.3	0.0
7. Nomex-410-4	869.9	164.7	366.7	93.5	694.3	143.8	346.5	81.7	3.5	0.5	2.4	0.1	3.1	0.2	2.0	0.1
8. Nomex-410-5	1995.8	210.5	689.7	85.6	1886.0	175.8	692.3	105.9	3.8	0.1	2.4	0.1	3.7	0.1	1.9	0.1
9. Nomex-414	273.9	80.4	183.0	39.2	235.3	60.8	171.9	30.7	2.5	0.1	0.8	0.1	2.4	0.2	0.6	0.0
10. Texoprint	113.7	20.9	161.5	13.7	111.1	18.3	145.1	12.4	3.9	0.5	1.4	0.2	3.1	0.4	0.8	0.1
11. Melinex-377	758.3[a]	431.5	605.4[a]	307.2	623.7[a]	261.5	---	---	3.9	0.3	4.0	0.3	3.6	0.2	---	---
12. Melinex-442	728.9[a]	438.0	476.6[a]	424.9	651.8[a]	503.4	367.4[a]	549.1	3.9	0.3	4.4	0.3	4.1	0.2	4.6	0.3

a. These Melinex values x 10

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The cost of maintaining an adequate supply of currency could be significantly reduced by increasing the circulation lifetime. The principal factor controlling lifetime is the deterioration of the mechanical properties, particularly flexure, of the currency substrate. It is well-known that synthetic polymers, either as coatings or laminates, can improve the flexure properties of paper. Also an entirely synthetic polymer substrate would be expected to result in a more durable currency. In addition to the choice of coatings or laminates there are a large number of synthetic polymers that may be suitable materials. Thus, the task of identifying a suitable system for currency is formidable without further selection criteria. We present here the final report of our joint effort with the Bureau of Engraving and Printing to develop such selection criteria.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Currency paper; laminates; physical and mechanical properties; synthetic papers

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