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QUALITY COMPARISONS OF TWIN-WIRE AND FOURDRINIER PAPERS

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ABSTRACT

A selective literature review reveals that, compared to comparable fourdrinier sheets, twin-wire papers tend to exhibit superior formation, substantially less two-sidedness, much reduced linting tendency, improved smoothness, improved basis weight and moisture profiles, uniformity and somewhat higher porosity. Roll formers tend to produce a somewhat grainy formation and more pin holes than fourdriniers, whereas twin-wires employing stationary dewatering elements provide a substantial reduction in pin holes at the expense of retention. Improved formation, strength and other sheet characteristics often accrue as a result of increased dewatering capacity, which can be utilized for operation at lower consistencies, with finer fabrics, at higher levels of refining or with more slowly draining furnishes. Improved profile stability is ascribed to better headboxes and the absence of surface waves.

INTRODUCTION

Twin-wire machines have become a standard of the industry for tissue and newsprint forming sections, and installations are rapidly increasing in certain other sectors as well. This phenomenon not only has affected the choice of twin-wires over fourdriniers for new paper machines, but also is manifested by the increasing number of top-wire rebuilds of existing fourdriniers.

The primary promises which twin-wires initially held out were increased speed potential and reduction of two-sidedness. In general, these promises have been amply fulfilled. In addition, other benefits which are commonly observed include improved formation and profiles, improved sheet surface characteristics, more compact installation, improved wire life, and reduced drive and vacuum requirements. On the negative side, however, there have been frequent complaints of poor retention, streaks, machine and fabric cleanliness problems, and limited versatility with respect to speed and basis weight. Many of these problem areas are being successfully addressed through modifications to both pure twin-wire and top-wire designs, and developments in headboxes, fabrics and other areas.

During the recent years of rapid twin-wire progress, much has been written about effects on paper quality. Comparisons between twin-wire and fourdrinier papers in the literature show substantial agreement and confirmation of experience. However, apparent contradictions do exist. This should not be surprising, since various aspects of quality are influenced by a diversity of design and operating parameters. This makes valid fourdrinier-twin-wire comparisons difficult. Moreover,

comparisons are further confounded by the lack of worldwide standards of testing and reporting certain paper quality characteristics.

The present paper attempts to review and summarize trends in paper quality differences reported from pilot and commercial twin-wire installations, as compared to sheets from fourdrinier machines. The scope is limited to single-ply paper grades. We will not consider units designed specifically to perform separate plies, and combine them by converging the wires.

CLASSIFICATIONS OF FORMERS

Prior to discussing quality aspects in detail, we will first attempt to classify formers in a manner which is relevant to paper quality differences. The following sections include brief mention of unique aspects of several classes of formers which may contribute to paper quality differences.

Fourdriniers

The forces applied on a fourdrinier to effect drainage by filtration act through the entire suspension thickness, from one side only. This is an obvious difference from a twin-wire design, which offers the possibility of water removal from both sides. The dewatering forces on a fourdrinier are not constant, but rather pulsating, and frequently have a reverse-direction component which tends to wash fines and fillers from the wire-side surface. This action is largely responsible for the relatively high two-sidedness characteristic of fourdrinier sheets. The action of foils, and especially table rolls, can become quite disruptive to formation at higher speeds. At moderate speed, however, the pressure pulsations and other wire "activity" can be very beneficial to formation, breaking up larger flocs, at relatively low table consistencies (1,2). Indeed, the lack of formation controllability with pure twin-wires, due to the immediate trapping and setting of the jet, places greater demands on the headbox. Actions taken on the fourdrinier table can compensate for a certain amount of medium-scale turbulence in the jet, but fewer options exist for dealing with large flocs with a pure twin-wire.

The landing of the jet on a fourdrinier wire may also contribute to differences from pure twin-wire sheet characteristics. A pressure forming situation obviously reduces retention and contributes to two-sidedness and wire mark. It also produces a certain turbulence which may influence formation, for better or worse (1,2). Furthermore, the squareness of the sheet is greatly affected by jet-to-wire speed ratio, and phenomena occurring immediately after jet landing. Fibers deposited near the wire are accelerated more, and therefore may tend to be more MD-oriented than those away from the wire (1,3). Hence, a Z-direction difference in fiber orientation may be observed in fourdrinier sheets, which is normally different from that seen in twin-wire sheets.

Pure Twin-Wire Formers

Listed in Table 1 are examples of several of the more popular twin-wire formers of the various classes. Included are "pure twin-wires", wherein a

free jet is injected between two wires, and hybrid formers, which feature a fourdrinier-type preforming section followed by a top wire for drainage in the opposite direction. The latter are also known as preformers or top-wire formers.

Pure twin-wire units can be classified into two major types, according to the elements used to define the forming zone. In roll formers, the jet is injected between two wires wrapping a solid or open forming roll. In contrast to the fourdrinier, dewatering occurs without pulsations, at a constant pressure equal to outer wire tension divided by roll radius (43,44). The jet is rapidly set in position, requiring a headbox which provides excellent fiber dispersion on a small scale. Dewatering may be two-sided at the forming roll if it is open. Relatively easy adjustment of the split of water removal between sides is possible if the forming roll is vacuum-equipped. Even with a solid forming roll, a subsequent S-wrap of the wire sandwich around a second roll permits water removal from both sides. However, some roll formers which are designed for low drainage resistance stock (towel or light-weight

tissue, for example) feature one-sided drainage around a solid forming roll only (Table 1).

Twin-wire formers which use stationary elements to define the forming zone (blade formers) make up the other major class of pure twin-wire machines. The blades over which the wires run create pulses, causing shear and turbulence in the forming zone. This potentially improves formation, but generally at the cost of poorer retention. Initial forming pressures are also relatively low, reducing wire mark and pinhole content (14).

Preformers

Preformers may be designed as new machines, or as retrofits to existing fourdriniers. As seen in Table 1, they employ rolls and/or stationary elements to effect top-side dewatering of the already-formed and partially dewatered sheet. Typically, the stock entering the twin-wire zone is at near 1% consistency, and it typically leaves at near 10% consistency to a zone of vacuum boxes (28). The percentage of upward drainage varies from 30-70%,

Table 1. Examples of pure and hybrid twin-wire formers

Machine Class	Machine Name	Manufacturer	Commercial Units sold*	References
Pure Twin-Wires				
Two-sided dewatering	Papriformer	Dominion Engr.	††	(4-10)
	Periformer MW	KMW	†	(4,11)
	Speed former	Valmet	†	(4)
	Duoformer C,E	Voith	††	(4,12,13)
Roll Formers				
One-sided dewatering	Duoformer T	Voith	†	(4)
	Beloit Tissue Former	Beloit	††	(4)
	Periformer LW	KMW	††	(4,11)
	Tisco Former	Escher-Wyss	†	(4)
Blade formers:				
	Bel Baie I, II	Beloit	†††	(4,5,14-16)
	Verti-Forma	Black-Clawson	††	(4,14,17-19)
Pressurized former:				
	Contro-Flo	Tampella	P	(4)
Preformers (Hybrids, Top-Wire Units)				
Between-wire dewatering on rolls only:	Dynaformer	Dominion Engr.	††	(4,20-22,39)
	Twinformer L	Escher-Wyss	P	(4)
	Duoformer F,H,L	Voith	††	(4,23-27)
	Periformer HR	KMW	P	(28,29)
	Bel Roll	Beloit	†	(4,37,38)
Stationary elements only:	Bel Bond	Beloit	††	(4,30,31,37)
	Akumat	A. Kufferath	†	(28)
Between-wire dewatering with both rolls and stationary elements:	Symformer F,N,R	Valmet	†††	(4,32-35,41)
	Top Flyte	Black-Clawson	†	(4,36,40,42)
	Bel Form	Beloit	†	(4,37)
	Alform M	Ahlström	P	(28)

* P = pilot or single mill installation.
 † = less than ten commercial units.
 †† = 10-35.
 ††† = more than 35.

depending on machine design and operating conditions (27,28). Preformers retain the controllability of formation inherent in a fourdrinier table while attaining some advantages of two-sided dewatering. Formation is also enhanced by the shear at the entrance of the wire convergence, which breaks up larger flocs. Relatively slow upward drainage velocities are maintained to minimize wire mark, backflow, disruption of formation, and to maintain good retention. As with other twin-wire machines, shear forces are also created in the stock if the wire sandwich reverses direction of curvature over various rolls. The proper magnitude of such shear may enhance formation and improve Z-direction bonding (8,28), but, perhaps more commonly, excessive shear in a relatively fluid center layer may destroy Z-direction bonding.

Twin-wire and top-wire installations and rebuilds afford increases in dewatering capacity, which different mills take advantage of in various ways. These include the obvious increases in speed and/or basis weight. In addition, it is often possible to increase refining or use other slower stocks for improved formation. The dewatering capacity may also be utilized to handle lower headbox consistency and thereby improve formation. Also, less open fabrics are often used to improve retention, and decrease wire mark and alter other surface characteristics. Hence, many of these changes, made possible by the twin-wire, affect the resultant sheet quality indirectly (through improved formation, different retention, etc.), rather than as a direct result of two-sided dewatering. These factors should be borne in mind in the following discussion.

PAPER QUALITY CONSIDERATIONS

Formation

In a comparison of several fourdrinier and twin-wire sheets, Sara (45) reported no significant differences in coefficient of variation of basis weight on a 0.1 mm scale, or in percent of small or large flocs. As Holik (46) has pointed out, very good formation is potentially attainable with all the types of formers. However, most observers of roll and blade type twin-wire machines have reported definite differences in the nature and quality of formation of the sheets, compared with fourdrinier-formed paper. Specifically, the formation from roll formers has been reported to be qualitatively more uniform than fourdriniers, particularly on a large scale (5,6,8). Roll-formed sheets, however, tend to have pronounced non-uniformity on a small scale. The intensity of this fine-grain formation can be deleterious with certain grades (4,6,8,14). Certainly the ability to reduce headbox consistency and different headbox designs may contribute to the reported differences in formation (11). Fine-scale microturbulence in the jet is associated with the production of very small flocs (graininess) at the expense of large flocs (14). In comparing blade formers with roll formers, Marcotte (5) and Wahlstrom (14) noted somewhat better formation on the machines with stationary elements. Gustafson and coworkers (15,16) have reported much finer scale formation on blade-former sheets than fourdrinier sheets, along with considerably less wire mark. Howarth, and others (18,19,47), used a

beta-radiographic method to measure the distribution of mass density of 1-mm square divisions in 5 x 5-cm paper samples. Fourdrinier sheets typically had a coefficient of variation of 10.0 to 10.4%, while for a blade-former paper the values were near 8.47.

Early pure twin-wire formers were reportedly plagued with streaking problems, but top-wire units exhibit less of that tendency, with generally equal or better formation as well (4,14). Anderson (29), Malashenko et al. (22), and Hauser (26) have reported the formation of roll-type preformers to be qualitatively superior to that of fourdriniers, and of a characteristically smaller scale. According to Futcher (20), a Dynaformer R rebuild of a fourdrinier machine, producing supercalendered roto news, improved the M/K formation, going from 6.3 to 10 units. A similar rebuild of a different fourdrinier producing TMP news saw the NUI formation (non-uniformity index) cut roughly in half (20,39). Again, however, both these comparisons were affected by reductions in headbox consistency after the rebuild, and the latter also involved the elimination of kraft long fiber in the furnish (20,39).

In evaluating formation improvements after a Sym-Former R rebuild, Hohns and Mauranen (32) utilized the "Valmet formation tester". In the case of a deinked news machine, the percent formation decreased (improved) from the 12-15% range to 10% after rebuild, although an increase in groundwood content in the furnish affects this comparison. A different fourdrinier, producing wood-containing fine paper, saw a decrease from 7.3 to 8.8%, down to 6.3 to 6.6%, after a Sym-Former R rebuild. Mauranen and Hujala (34) analyzed formation after a similar rebuild of a machine producing 70 gsm wood-free fine paper, and reported standard deviations of basis weight variation for various floc sizes. The largest improvements were seen in intermediate (1-5 mm) and large (5-50 mm) flocs. Carson (36) noted similar levels of improvement in a "relative formation index" for a Top-Flyte former (13.7) and a Verti-forma (13.6), as compared with a fourdrinier (5.0-6.0). Other authors (41,42) recently reported improvements in "NUI formation" after a Top-Flyte rebuild, going from 10.2 to 10.6 before, to 7.9 to 8.7 after.

It is evident from the above that valid quantitative comparisons of formation are difficult to carry out. This arises from both the difficulty in maintaining identical controlled conditions with fourdrinier and twin-wire machines, and from the lack of a standard means of assessing formation. Nevertheless, certain trends are clear. Roll formers improve uniformity of larger-scale formation, but lock in the sometimes objectionable graininess thought to be characteristic of high microturbulence in a headbox jet. The action of blade formers is apparently capable of redistributing some of those smaller flocs. Top-wire machines consistently show formation improvements over fourdriniers. This is apparently because of the shear and controlled turbulence at the wire convergence, and at dewatering elements. Brauns (37) reports that stationary top-wire dewatering elements afford greater potential formation improvements than those with rolls only. Twin-wires have the potential of producing a much less intense wire mark than the fourdriniers, although the latter still have the

apparent advantage of one side with no wire mark at all.

Sheet Strength Properties

Comparison of strength properties of machine-made sheets are obviously affected by many of the same uncontrolled parameters influencing formation comparisons: furnish, degree of refining, etc. Moreover, strength is also very strongly affected by formation itself (48), as well as by the anisotropy of the sheet (46). In addition, improved formation may reduce the amount of calendering needed to attain the desired uniformity of caliper and surface properties, thereby influencing the sheet bulk and other physical properties (47). It may, therefore, be no surprise to find conflicting reports in the literature concerning the effect of twin-wire forming on sheet physical characteristics and strength.

Listed in Table 2 are examples of published sheet quality data, wherein direct comparisons are made between various twin-wire and fourdrinier-formed papers. In most of these cases, the comparison is a reasonably valid one (same mill, same furnish, etc.); most of the top-wire comparisons consist of data obtained before and after a rebuild. Unfortunately, the methods of measurement are not always the same, and sometimes units are not even given.

Pure twin-wires are sometimes reported to give sizable improvements in tensile and burst if there is greater anisotropy (6,46), or improved formation (9,11). More typically, however, the comparisons show fairly small changes in these properties (10,15), and in CD tear (10,17,49). Bulk may be lower if the twin-wire sheet shows increased bonding. As mentioned above, however, a reduction in the amount of machine calendering needed for uniform caliper on the twin-wire sometimes produces higher bulk (47). Moreover, bulk is very much affected by Z-direction distributions and other factors influencing porosity, as discussed later.

With regard to internal bonding, some workers (50,51) have reported weak spots in the center of pure twin-wire sheets. Gustafson and Dennis (15), on the other hand, reported that an early blade former produced higher Z-direction tensile than fourdrinier sheets. Apparently, any differences in this regard are usually inconsequential for practical purposes (50), provided excessive shear is not encountered in the sheet center while it is still very fluid.

With top-wire machines, bonding related properties (tensile, burst, sheet density) have been reported as higher (20-22,27-29,33,34,41), lower (20,24,31), and about the same (22,23,30) as fourdrinier properties. A similar variety of results have been reported for internal bond (22,24,26) and tear strength (20,22,30,31,33,46). Stretch is commonly observed to be higher with top-wire formers than fourdriniers, presumably because of improved profile and formation (21,29), although increases in speed and overall machine draw may reduce stretch (33,41).

Retention

One of the most commonly reported drawbacks of twin-wire machines is reduced retention, which burdens fiber recovery (51), limits the basis weight of filled sheets (52), hinders internal sizing (50), etc. It was pointed out by Britt that increased turbulence during drainage causes the retention to drop (53). He also showed that the final consistency of the sheet increases slightly with an increased level of turbulence (54). Neogi (55) noted that retention depends very much on turbulence and small particle "washout" during early forming, especially over stationary elements. Accordingly, roll formers often exhibit higher first-pass retention than fourdriniers (8,13,49), while blade formers are particularly deficient in this regard (5,14,49). As expected, top-wire formers lie between these extremes. The top-wire-fourdrinier comparison very much depends on the presence and intensity of stationary element effects (20-23,26-28,32-34). Unfortunately, commercial retention comparisons are often confounded by switching to double-layer fabrics on the twin-wire, and by furnish changes, use of retention aids, etc. Nevertheless, there seems to exist a trade-off situation between high retention and good formation.

Although retention has mostly indirect effects on sheet quality, it correlates generally with Z-direction distribution of fines and fillers. This dramatically influences surface characteristics, two-sidedness, porosity, etc. Listed in Tables 2 and 3 are additional fourdrinier-twin-wire comparisons pertaining to these and related characteristics.

Two-Sidedness

The ability of twin-wires to minimize the two-sidedness characteristic of fourdrinier sheets is widely documented. Even in this case though, there are factors which would tend to blur the distinction between machine designs. Clearly, press felting and other operating parameters can either improve or worsen two-sidedness (56). In addition, some fourdriniers are worse than others (depending on nature of table elements, speed, etc.), and some twin-wire sheets are fairly two-sided (52). In fact, a Scandinavian survey (57) failed to detect any significant difference in two-sidedness of commercial fourdrinier vs. twin-wire newsprint. According to Wahren et al. (44), two-sidedness is more affected by pressure and flow pulsations than by drainage symmetry.

Nevertheless, there is widespread agreement that twin-wire formers of all types generally deliver to the press section much less two-sided sheets, compared with the typical fourdrinier. This has been quantitatively expressed as Z-direction ash or filler distributions (6,12,13,16,25,26,34,47,50), fines and fiber distributions (13,28,35,36,42,50), or Z-direction distribution of filtration resistance (15,16,32,55). These distributions affect the smoothness of the respective sides of the sheet (10,13,17,20,26,27,32,39,42,47), as well as the oil absorption (13,23,27,32); twin-wire sheets tend to be much less two-sided with respect to these properties as well. Generally, the levels of twin-wire smoothness tend to lie between those of a comparable

fourdrinier top side and wire side, while fourdrinier felt-side oil absorption is generally improved by two-sided dewatering. These variables depend, of course, on those same factors which affect retention and particle distributions, as well as on the calendering applied. Ultimately, the lower two-sidedness, and especially the lack of a heavily wire-marked fines-deficient surface common from fourdriniers contribute to superior printability of sheets from twin-wire machines of all types (5,23,32).

Linting

Another widely-documented twin-wire benefit, particularly important with offset printing papers, is linting tendency (5,20,21,28-31,33,36,38,40,47,49). According to Wood and Karnis (58), fourdrinier sheets are prone to high linting, especially on the felt side, when there is a high concentration of low specific surface, low bonding "lint candidate" material on that surface. The distribution of low specific surface particles in twin-wire sheets tends

to show a deficiency on both sides, and hence lower linting. As noted above with other Z-direction distributions, some fourdrinier sheets are indistinguishable from twin-wire papers (57,58), but those appear to be the exceptions. Observations similar to those for linting have been noted for pick resistance (10,26,27,30,50,59): fourdrinier felt sides tend to be worst, although some fourdrinier sheets are as good as twin-wire papers. It is not uncommon, however, for a fourdrinier top side to require a starch spray in order to meet off-set printing requirements (26,50).

Pinholes and Porosity

A serious problem encountered with roll formers has been a large pinhole area in the sheet (27). However, other types of twin-wire machines typically produce fewer pinholes relative to fourdrinier sheets (14,24,26,27,46).

Consistent with this is the fact that twin-wire machines without stationary elements commonly

Table 2. Comparisons of twin-wire and fourdrinier papers*

Former Type	Duoformer C	Papriformer	Duoformer F	Duoformer F	Dynaformer R	Dynaformer R	Dynaformer R	Bel Bond	Sym-Former R
Furnish or grade	Newsprint	Offset news: 72% SGW, 17% TMP, 11% SBK	SC printing: 14.0/14.6% ash	Printing: 19% kraft, 64% SGW, 15% deinked 3% filler	Newsprint: RMP kraft	Supercal-endered roto newsprint	TMP news-print 0/3.8% kraft	Fine papers HW sulfite SW kraft wood-free	Newsprint 50% SGW 30% TMP 20/17% kraft
Headbox cons. (%)	0.74/0.67				0.67/0.78	0.70/0.72	0.66/0.80		48.8
Reel moisture (%)							7.3-7.5/6.92		8.0-8.5/7.5
Basis weight (g/m ²)	55/55.3	48	59/56	40	48.8	48.8/51.6	48.8		
Tensile MD		2.87	2900/2750	3820/4345	1.925/2.201	2.9/2.67	2.18/2.4		1.92/1.80
Tensile CD				1700/1940	0.787/0.903			47/38	250/253
Tear MD		26-28/25-27	mJ/m		275/275			47/38	240/326
Tear CD			513/479		412/412		16.6/17/2	47/38	73/69
Burst		6.7-7.8/7.0-8.3			69/76		65-68/77.8	no change	73/69
Stretch (%)					0.95-1.05/1.04	1.2/1.1			1.14/1.27
Bulk (cc/g)			0.979/1.067	1.63/1.59					
Caliper	97/93	3.4-3.5/3.3-3.4			84.3/85.3	58/58	82.7/86.1		
% Retention	72/65				59.9/67.8	55-65/62.6	65/61		57/61
% Pinhole area				0.014/0.021					
Porosity	Gurley, sec/100 cc 10/13			Bendtsen, mL/min 260/224		Bendtsen 65/53	cc/min 106/86.1	no change	353.6/305.3
Oil Absorption TS	40/43								
Oil Absorption BS	37/37								
Smoothness TS	Bekk sm., sec 28/45		Smoothness sec 760/590		Sheffield sm. 115/123			Sheffield sm. 80-140/110-190	
Smoothness or Roughness BS	27/39	120-130/105/120	750/485		115/116				
Linting or surface pick		IGT pick resist.	Pick resist.			Lint propensity 10/50-70		Wax pick	Brush test
Linting or surface pick TS			11/9			10/30		16-18/12	90/150
Linting or surface pick BS		8.0-9.5/3.0-7.5	11/11					16-18/16	
Reference	(13)	(10)	(27)	(24,26)	(20)	(20,21)	(20)	(30)	(33,41)

*First number of each entry is the twin-wire value, followed by a slash and the comparable fourdrinier value. If only one number is given, the value was then the same for both machines.

produce higher bulk and porosity relative to fourdriniers (13,20,21,23,24,26,27,32-34,39,41,42,50). Apparently the gentle dewatering and more uniform Z-direction distributions from formers without stationary elements are responsible for this (14, 31,50). (Because of the different structure of a twin-wire-formed sheet, however, a porosity increase may not necessarily correlate with strike-through on printing.) In contrast, blade-formed papers may exhibit increased density relative to comparable fourdrinier sheets (14). This may be associated with a concentration of fines near the sheet center, or simply due to improved formation (22,28).

Profiles

In most cases, the residual variation in basis weight of twin-wire-formed sheets is substantially lower than that of comparable fourdrinier sheets (11,13,17,18,28,30,38,47,50). Some of this improvement is undoubtedly due to differences in headboxes or other factors, but apparently not all of it (18,

47). Comparisons of CD and MD profile components with those of fourdrinier sheets gives mixed results: sometimes better (17,50), sometimes not (42, 50). Early twin-wire problems with CD streaks have been successfully dealt with through fabric improvements and the use of bowed rolls. The absence of surface waves on pure twin-wire machines greatly improves CD controllability and eliminates the amplification of headbox pulsations common on fourdriniers. Twin-wire improvements in basis weight uniformity have translated into less calendering needed for uniform caliper (higher bulk) (33,47), and potentially higher reel moisture by eliminating the need to overdry heavy spots (47). Indeed, Brauns (30) and Kurylłowicz (39) report improvements in moisture profiles with top-wire units.

CONCLUSIONS

Table 4 provides a qualitative summary of twin-wire sheet quality characteristics relative to fourdrinier papers, based on the foregoing review. We have seen that, compared to comparable

Table 3. Comparisons of preformer and fourdrinier papers*

Former type	Duoformer F	Duoformer F	Duoformer F	Duoformer H	Bel-Bond	Symformer R	Top-Flyte
Furnish or grade	Telephone Directory	Offset news 8.8/8.6% ash	Offset news	Newsprint 10.3/9.3% filler	Fine paper, wood-free 11.7/11.1% ash	Newsprint 12/12% kraft 63/73% deink 23/15 SGW	Newsprint 68% SGW 26% HYS 6% SBK
Headbox cons. (%)							0.83/0.74
Basis weight (g/m ²)	36/36	51.5/52	40.9/41.0	48.8/48.9		45.4/47.1	48.8
Bulk (cc/g)	2.12/2.0		1.63/1.59				
Caliper							78/74
% retention		59/57	64/66	59/57		59.5/62-64	59/63
% pinhole area	0.28/0.64		0.14/0.21				
Porosity	mL/min 137/155		mL/min 260/224	Bendt air permeability 2.39/2.10			mL/min 421/337
Oil absorption	TS BS	g/m ² 21/13 25/25		g/m ² 19/16 22/25		PATRA 59/60 58/50	
Smoothness or Roughness	TS BS	Roughness 127/105 110/144		Bendtsen rough. 123/114 99/104	Bendtsen sm. (sec.) 120/240 130/260	BEKK sm. 66/65 61/49	PPS-S10 sm. 3.7/4.0 3.9/4.2
Linting or Surface pick	TS BS				wax pick 18/13 18/18		Apollo linting 5.6/6.8 4.8/6.6
Reference	(27)	(27)	(27)	(23)	(37)	(32)	(40,42)

*See footnote, Table 2.

fourdrinier sheets, twin-wire papers tend to exhibit:

- superior formation
 - roll formers tend to lock in a graininess characteristic of high-turbulence head-box jets
 - formation is often enhanced by decreases in consistency, or furnish changes, which are made possible by the increased dewatering capacity
- small but inconsistent strength improvements
 - very dependent on improvement in formation relative to the fourdrinier baseline case
 - very dependent on squareness or anisotropy, which can be more easily varied over a wider range with twin-wires
- small but inconsistent changes in bulk
 - very dependent on calendering, and Z-direction particle distribution
 - pulsating dewatering tends to decrease bulk, constant pressure dewatering tends to increase it somewhat
- substantially less two-sidedness
 - with respect to particle distributions, smoothness, oil absorption
 - can be controlled to some extent by dewatering split top/bottom but more by amount of pulsations on the two sides, and by press felting
- much reduced linting tendency
 - a consequence of concentrating low specific surface material in the center of the sheet
 - dewatering pulsations beneficial to some extent

- improved smoothness
 - both sides tend to be between typical fourdrinier top and felt side values
- somewhat higher porosity
 - affected by calendering, formation, etc.
 - tendency less pronounced with pulsating dewatering and resultant non-uniform Z-distributions
- substantial reduction in pinholes with stationary elements
 - opposite effect - more pinholes - with pure roll formers
- improved basis weight and moisture profiles
 - much affected by headbox design, operation, etc.

So the absence of pulsations and of many quality differences are a direct result of two-sided dewatering. Some of the effects, however, come about indirectly, as a consequence of the several ways in which increased twin-wire dewatering capacity can be utilized. Hence, twin-wire machines may permit increased machine speed, lower headbox consistency, use of slower-draining stocks, and use of finer-surfaced fabrics. These factors may then influence formation, sheet strength and surface characteristics, etc. Improvements in these areas, in turn, may then permit further changes in operation which favorably influence other properties (decreased calendering requirement, for example, to give higher bulk). Hence, the actual difference in twin-wire paper quality, relative to that of fourdriniers, depends on how the mill capitalizes on the twin-wire dewatering capacity. The overall picture is one of considerable potential quality enhancement, as indicated by the majority of pluses in Table 4. As mentioned previously, many of these benefits are

Table 4. Quality characteristics expected with twin-wires, relative to fourdriniers

	Pure Twin-Wires		Top-Wire Units	
	Roll formers	Blade formers	Dewatering primarily over rolls	Substantial stationary element pulsation
Formation	+	++	+/**	++
Strength properties	o/+	o/+	o/+	o/+
Bulk	o/+	o/-	o/+	o/-
Two-sidedness	+/**	++	+/**	++
Linting	+/**	++	+/**	++
Smoothness	+	+	+	+
Porosity	-	o/-	-	o/-
Pinholes	o/-	++	+	++
Basis weight profiles	+	+	+	+

- ++ = substantial improvement
- + = slight to moderate improvement
- o = no significant or consistent effect
- = slight to moderate deterioration

realized at the expense of retention, and, in some cases, cleanliness and other twin-wire drawbacks. Nevertheless, from a paper quality standpoint at least, the future growth of twin-wire machines seems assured.

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