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HIGH CONSISTENCY FORMING PROCESS FOR
PAPERMAKING

Part I: A Research, Development, and Demonstration
Program Plan for the U. S. Papermaking Industry

Final Report

By
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April 1980

Work Performed Under Contract No. AC02-78CS40150

Thermo Electron Corporation
Waltham, Massachusetts

U. S. DEPARTMENT OF ENERGY

Division of Industrial Energy Conservation

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PART I

A RESEARCH, DEVELOPMENT, AND
DEMONSTRATION PROGRAM PLAN FOR
THE U.S. PAPERMAKING INDUSTRY

Final Report
April 1980
Sherif S. Fam and Michael Judd

Prepared for
U.S. Department of Energy
Washington, D.C.

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ABSTRACT

This report addresses the subject of research, development, and demonstration (RD&D) of energy conserving technologies applicable to paper-making operations downstream of the pulping process. An RD&D Program Plan is presented based on a survey of leading representatives of the papermaking industry, equipment manufacturers, consulting engineering firms, the American Paper Institute, and the Technical Association of the Pulp and Paper Industry. For perspective, the program plan is presented against the general background of the industry's current issues and concerns.

ACKNOWLEDGMENTS

The authors are greatly indebted to their many colleagues in industry who generously contributed time and effort to this study and to Mr. John Rossmeissl of the DOE for his guidance and support.

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1. INTRODUCTION

The program "High Consistency Forming Process for Papermaking" deals with energy conserving opportunities in the formation of paper and paperboard. The program consists essentially of two parts. The objective of the first part is the preparation of a program plan for research, development, and demonstration of technologies that would improve the efficiency with which energy is used in papermaking operations downstream of the pulping process. The plan should have a broad base of industry support and must take into account the mutual interactions between energy conservation, product quality, and the financial implications of equipment and process changes in the mill. The study also includes an investigation into the possibility of establishing a central research and development facility that would serve the paper industry's technological needs. Such a facility could benefit the industry in a number of ways. It would help introduce new process technologies - such as novel forming processes - at substantially less development cost to the industry. Some of these technologies could provide additional benefits in the form of reduced environmental burdens and reduced capital costs per unit of product capacity. From the national viewpoint, the facility would contribute to the conservation of the country's energy and material resources.

The second part of the program deals with the development of a high consistency headbox, and the design, layout, and costing of an instrumented test facility supported by a basis of experiments on headbox hydraulics, sheet delivery systems, and stock drainage characteristics. The work done in this part of the program is covered in a separate report which also deals with the subject of the central RD&D facility investigated in the first part. This report describes the balance of the work done in the first part of the program during the period February 1978 to January 1979.

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2. METHODOLOGY AND APPROACH

The basic instruments used to develop the RD&D program plan were (1) a literature search to provide background information on the most recent developments in papermaking technology and areas of active interest or concern, and (2) a survey of leading representatives from all segments of the papermaking community, including paper manufacturers, machine and equipment suppliers, and engineering consulting firms.

The survey was conducted by personal interview, telephone discussions, and by mail. The main focus of the survey was on energy conserving techniques and novel technologies that are within the realm of the attainable in the near-to-intermediate term (1985-1990). The responses from a first round of discussions were used to prepare a preliminary draft program plan which was then circulated for comments and review to a wider audience of industry representatives, including those associated with the American Paper Institute (API), the TAPPI R&D Subcommittee, and the Institute of Paper Chemistry. The principal investigators of this study were invited to attend the September 1978 meeting of the TAPPI R&D Subcommittee in San Francisco where they presented their initial findings to the individual members. Later, they attended the plenary meeting of the TAPPI Energy Committee. All respondents to the survey were invited not only to discuss in broad terms their particular concerns and perceptions of the relative utility of alternative technological directions or advances in process technology, but also to comment as much as possible in specific terms on the particular items contained in the draft program plan, and to suggest specific alternatives that would more closely reflect their judgment of useful directions to follow in the near-to-intermediate term.

We have attempted in this study to provide the DOE with a broadly supported list of fuel saving technologies that, once developed, appear most likely to be adopted by the paper industry. The latter criterion is important since the pace and level of market penetration are ultimately the

measures by which the success of RD&D projects will be gaged. The dispersion of energy conserving technologies, however, is not solely a function of their perceived individual merit.* The intensity and direction of technological development is often vitally affected by issues of the day and the resources available to industry to pursue the alternatives available to it. Consequently, it is necessary to consider the RD&D program plan for paper forming against the broader background of industrial issues and concerns.** We believe that the perspective gained from this approach would be useful to the DOE in its deliberations on the scope and timing of RD&D projects.

We begin with a general analysis of the financial position of the U.S. pulp and paper industry and its capital commitments to energy conservation, pollution abatement, and capacity expansion. This is followed by a survey review of the major issues affecting the direction of the industry and its allocation of resources. An RD&D program plan for paper forming is then presented with a discussion of the technologies involved and the benefits that can be expected from their development and commercialization.

*With the possible exception of process technologies that simultaneously promise increased production. Such technologies are likely to receive more immediate attention.

**In our October 1978 presentation to the DOE we noted the concern over environmental restrictions and predicted an accelerating trend toward the substitution of wastes for residual oil. Since that time, the contribution of wastes to total primary energy increased from 46 percent in 1978 to 49 percent in 1979, a rise of three percentage points compared with the historical average rise of one percentage point per year for 1975-1978.

3. CAPITAL COMMITMENTS OF THE INDUSTRY

3.1 CAPITAL EXPENDITURES FOR ENERGY CONSERVATION

Although the pulp and paper industry is well along the way to fulfilling its voluntary commitment to energy conservation, there is virtually no information on the capital it has spent to that end. A major reason why the data are not available is that energy-specific costs cannot readily be disaggregated in an unambiguous manner from the totality of plant and equipment expenditures, which are predominantly multifunctional. The only figures available on the subject are the original estimates of Ford, Bacon, and Davis¹ (Table 3.1).

3.2 CAPITAL EXPENDITURES FOR POLLUTION ABATEMENT

A considerable amount of capital has been spent by the primary sector of the industry to satisfy environmental guidelines for water, air, and solid wastes. The National Council of the Paper Industry for Air and Stream Improvement Inc. (NCASI) has determined from its surveys that the annual expenditures for the years 1972 through 1976 represented an average of 29 percent or greater of total capital outlays.² As a result, the URS study,³ prepared for the API in 1975, concluded that pollution abatement expenditures would exacerbate the already existing problem of capital formation in the industry caused by an intensifying cost inflation and a relatively strong consumer demand. The URS study assumed a growth rate of 3.8 percent per year over the 1974 level; current estimates,⁴⁻⁶ however, are more modest (2 to 2½ percent per year over 1974). Such lower growth rates would ease the problem of capacity shortage and tend to lessen the upward pressure on product values. Nevertheless, pollution abatement expenditures may be expected to play an important part in plant expansion decisions in the future. The amendments to the environmental protection guidelines introduced in December 1977 could provide some relief, but, as of this date, they are still subject to interpretation and debate.⁷ There are some indications that changes in the New Source Performance Standards are currently

TABLE 3.1
ESTIMATED CAPITAL COSTS AND ENERGY SAVINGS*
1976 to 1980

Measures	Savings (Trillion Btu)	Capital Cost (\$ Million)
Batch Digester Computer Control	13.6	50.4
Lime Kilns	0.2	0.5
Lime Mud Filters	3.5	11.0
Flue Gas Waste Heat Recovery	6.9	23.6
Combustion Controls, O ₂ Analyzer and Excess Air	4.3	1.7
Boiler Feedwater Heating	18.6	20.5
Paper Machine Computerization	5.0	27.0
Optimize Paper Machine Dryer Section Hood System	13.2	34.7
Reuse Mezzanine Air	<u>3.7</u>	<u>6.9</u>
Total	69.0	176.3

*Capital cost figures do not include investments in more efficient capacity expansion equipment. The total amount of capital necessary to achieve the target savings was estimated¹ at \$250 million (1976).

being considered along with other modifications to the 1977 amendments to the Clean Air Act in order to alleviate inflationary pressures.⁸

The historical data on capital expenditures for pollution abatement are shown in Table 3.2, along with expected expenditures for 1978 and 1981. These data do not include annual operating, fixed, administrative, and research costs which are given in Tables 3.3 and 3.4. The relationship between pollution abatement expenditures and total capital expenditures is shown in Figure 3.1.⁹ The most recent McGraw-Hill survey¹⁰ estimates that, as of January 1, 1978, an additional \$1.2 billion of capital needs to be spent by the industry to bring its present facilities in line with current guidelines for 1984 (i.e., excluding the proposed amendments of 1977).

3.3 CAPITAL COMMITMENTS FOR PLANT IMPROVEMENTS AND CAPACITY ADDITIONS

The updated¹¹ annual capacity survey of the API for 1977⁵ gives the industry's current annual capacity and plans for capacity additions (Table 3.5) based on public announcements. Comparing the past performance of the industry¹² with the short term trends for 1978-1980 (Table 3.6), we see that the largest growth rate is in newsprint, followed by tissue and paperboard. A significant decline in the growth rate of construction paper and board is expected along with a decrease in capacity for packaging and industrial converting papers. The overall growth in capacity of the industry during that period is expected to average 2.5 percent. These short term trends, however, are not necessarily indicative of a future growth pattern. In addition, the cyclical nature of the industry¹³ precludes the indiscriminate extrapolation of short term behavior into the future. There are some¹⁴ who believe that the historical 3-year cyclical pattern (based on retained earnings) is likely to shorten in the future with more abrupt savings in earnings.

The evaluation of capacity-related investments depends upon the product structure as well as on the distribution among "greenfield" expansions

TABLE 3.2
CAPITAL EXPENDITURES* (MILLIONS) FOR POLLUTION ABATEMENT
PULP AND PAPER INDUSTRY

		1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978 ^(e)	1981 ^(e)
Air	(a)		44	43	74	120	134	205	179	216	286	319	238		
	(b)					59	122	172	275	253	401	271	178	189	134
	(c)									308	273	182			
	(d)									271	323	181			
Water	(a)		31E	43E	52E	65E	66	129	162	296	341	216	127		
	(b)					94	135	149	149	175	236	441	208	129	167
	(c)									158	189	304			
	(d)									193	266	279			
Solid	(a)		1E	1E	2E	2E	2.5	5	10	11	18	29	30		
	(b)					NA	NA	NA	NA	NA	9	128	50	73	62
	(c)									25	27	25			
	(d)									13	16	27			
Total	(a)		76	93	128	187	203	339	351	523	645	564	395		
	(b)		94	82	143	153	257	321	424	428	646		436	391	363
	(c)									491	189	511			
	(d)									477	505	487			
Cum. Total	(a)	352	428	521	649	835	1039	1378	1729	2252	2397	3461	3856		
	(b)	352	446	528	671	824	1081	1402	1826	2254	2900				

*Excluding operating, fixed, and administrative costs

E Estimated Distribution

NA Not Available

(a) NCASI Special Report No. 77-06, August 1977

(b) McGraw Hill: "Historical Pollution Control Expenditures and Related Data," Revised 1977
 "Eleventh Annual Survey of Pollution Control Expenditures," May 15, 1973

(c) Bureau of Economic Analysis Data as reported in (d)

(d) Census: "Pollution Abatement Costs and Expenditures 1976," December 1977

(e) Planned - From (b)

TABLE 3.3
PULP AND PAPER INDUSTRY ENVIRONMENTAL PROTECTION
OPERATING, FIXED, ADMINISTRATIVE,
AND RESEARCH COSTS - 1976

	Million Dollars	
	Subtotal	Total
OPERATING COSTS		
1976 - Includes direct operating costs of environmental protection facilities, e.g., power, labor, maintenance and, where applicable, payment to public agencies for treatment in municipal systems		295 (P)
FIXED COSTS		
1976 - Depreciation on environmental protection expenditures	211	
Interest on environmental protection expenditures	250	
Taxes on environmental protection expenditures	15.1	476.1
ADMINISTRATIVE COSTS		
1976 - Administrative expenses not charged to mill operating cost	44	44
RESEARCH EXPENDITURES		
1976 - Industry conducted and supported environmental protection research	12.5	<u>12.5</u>
		827.6

(P) Provisional - Subject to change upon completion of NCASI 1976 Operating Cost Survey.

Source: NCASI, Reference 2

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TABLE 3.4
SUMMARY OF ENVIRONMENTAL PROTECTION
ANNUAL CHARGES - 1976

	Million Dollars	\$/Ton Paper and Paperboard
1975	706	12.6
1976 Operating Costs	295	
Fixed Costs	476	
Administrative Costs	44	
Research	13	13.00
Total	828	

Source: NCASI, Reference 2

Figure 3.1 Capital Expenditures in the Paper Industry

TABLE 3.5
ANNUAL CAPACITY
ALL GRADES PAPER AND PAPERBOARD
(Thousands of Short Tons)

Year	Net Additions During Year	Annual Capacity	Percent Increase
1956	1,409	34,095	4.3
1957	2,091	36,186	6.1
1958	1,810	37,996	5.0
1959	1,441	39,437	3.8
1960	1,346	40,783	3.4
1961	1,284	42,067	3.1
1962	1,045	43,112	2.5
1963	935	44,047	2.2
1964	1,414	45,461	3.2
1965	1,701	47,162	3.7
1966	2,580	49,742	5.5
1967	2,953	52,695	5.9
1968	2,415	55,110	4.6
1969	2,197	57,307	4.0
1970	1,355	58,662	2.4
1971	1,165	59,827	2.0
1972	2,041	61,868	3.4
1973	2,663	64,531	4.3
1974	1,582	66,113	2.5
1975	716	66,829	1.1
1976	1,355	68,184	2.0
1977F	1,229	69,413	1.8
1978F	1,705	71,118	2.5
1979F	2,073	73,191	2.9
1980F	1,656	74,847	2.3

F - Forecast

Source: American Paper Institute

TABLE 3.6
U.S. PULP, PAPER, AND PAPERBOARD CAPACITY
AVERAGE ANNUAL GROWTH

	Annual Capacity (1977) (millions of tons)	Annual Growth (Percent) 1970-1977	Estimated Annual Growth (Percent) 1978-1980
<u>Paper</u>			
Printing, Writing, etc.	15.0	2.9	2.8
Packaging and Industrial			
Converting	6.2	1.0	(0.5)
Tissue	4.6	2.4	4.0
Newsprint	4.1	2.9	4.4
Total Paper	29.9	2.4	2.5
<u>Paperboard</u>			
Unbleached Kraft	14.8	2.9	3.2
Recycled	8.8	0.7	1.8
Semi-Chemical	4.8	3.1	3.6
Solid Bleached	4.1	2.2	3.6
Total Paperboard	32.5	2.1	3.0
<u>Construction Paper and Board</u>	7.0	3.8	0.6
Total All Above Grades	69.4	2.4	2.5
<u>Total Wood Pulp</u>	54.4	2.4	2.7

Source: American Paper Institute^{5,11}

(i.e., brand new plants), site expansions, and plant improvements. The most recent estimates of the distribution and costs of these capacity additions^{15,16} are given in Table 3.7. It is important to note that the particular product/process combination adopted for these estimates is somewhat different from that given by the API (Table 3.6). For the purposes of this study, however, these figures may be used as a guide since the intention here is not to develop an accurate forecast but rather to estimate the extent to which technological changes may be financed by the industry in the near term.

Based upon the capacity expansion pattern shown in Table 3.8, Firth¹⁶ gives a forecast of cash flow for the period 1978-1985 (Table 3.9) which shows no capital short-fall despite the large increases in capital costs. This is partly due, of course, to the rather low growth rate (~2 percent) of capacity additions.

The industry's product prices have generally not kept up with inflation. The average annual price increase during the last 5 years was about 2.8 percent. But this situation appears to be changing, too. Paperboard prices are now about \$220/ton compared with \$185/ton last year, an increase of 19 percent. Demand is running ahead of supply in newsprint, paperboard, and printing and writing paper. There is also room for greater capacity utilization. The API recently reported that the capacity utilization during the first half of 1978 was 93.4 percent compared with 95.3 percent for the same period in 1972.

Inflation is, of course, a concern but it need not always be harmful if it is moderate because the industry is capital intensive and inflation affects the variable costs. So the industry can still operate profitably if product prices increase at or slightly below the inflation rate because fixed charges contribute more to product costs than variable charges.*

*This assessment was made in 1978 but it still holds today despite the much higher inflation rate, provided the anticipated recession is not severe.

TABLE 3.7
WEIGHTED AVERAGE CAPITAL COST FOR INSTALLING PRODUCTION CAPACITY
 (Basis: 1977 dollars)

Type of Installation	Percentage of Additional Capacity	Capital Cost (% of Greenfield)	\$ per Annual Ton	
			Unit Cost ²	Wgt. Avg.
PERIOD 1978-1980				
Greenfield	10 ¹	100	775	80
New machines at existing sites	50 ¹	85	660	330
Machine improvements	40 ¹	35	270	<u>110</u>
				520
PERIOD 1980-1985				
Greenfield	30	100	775	230
New machines at existing sites	35	85	660	230
Machine improvements	35	35	270	<u>100</u>
				560

¹Estimates reported by American Paper Institute.

²Fixed capital only; does not include working capital.

All estimates rounded off.

Source: Reference 15

TABLE 3.8
CAPACITY EXPANSION FORECAST FOR THE PAPER INDUSTRY
(Thousands of Annual Tons)

	1979-1980	1980-1985	1978-1985 Total
Grassroots	460	2,350	2,810
New Machines	2,330	2,750	5,080
Net Improvements	<u>2,020</u>	<u>2,750</u>	<u>4,770</u>
Total Additions	4,810	7,850	12,660
Replacement Tonnage	<u>1,170</u>	<u>1,800</u>	<u>2,970</u>
Total Construction	5,980	9,650	15,630

Source: Reference 16

TABLE 3.9
CASH FLOW FORECAST 1978-1985
 (\$ million of 1977 dollars)

	1978-1980	1981-1985	Total
Total Production ¹	191,400	344,900	536,300
Sales Revenue	67,300	131,500	198,800
Sources: Net Income	5,340	10,430	15,770
Depreciation	<u>4,500</u>	<u>11,500</u>	<u>16,000</u>
Total	9,840	21,930	31,770
Uses: Investment	7,370	12,570	19,940
Working Capital	<u>290</u>	<u>340</u>	<u>630</u>
Total	7,660	12,910	20,570

¹Production in thousands of tons.

Source: Reference 16

In conclusion, the financial picture appears encouraging for the general development of process technologies, particularly those multibenefit process improvements that permit increases in production capacity along with reductions in purchased energy use or environmental outlays.

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4. SURVEY RESULTS

4.1 GENERAL DISCUSSION

The companies that we contacted during our survey (Table 4.1) cover the full range of products manufactured by the industry. The combined capacity of these companies is estimated at slightly less than 50 percent of the total capacity of the industry. Furthermore, these companies are leaders in energy matters and are represented in key API and TAPPI Committees.

The prevailing view of most of the respondents to our survey was that the cause of energy conservation would best be served in the near term by providing economic incentives to industry and removing the regulatory disincentives to the use of currently available technologies.

Suggestions for economic incentives included low or no interest loans, higher investment tax credits (in the order of 30 percent), and government participation in projects whose paybacks exceed 3 years. A specific recommendation for this class of projects was the promotion of cogeneration by encouraging industry to install high pressure power and recovery boilers.* Another recommendation was the central banking of a portion of the revenues obtained in good business years for use in energy conservation projects. This incentive was initiated in Sweden some time ago. It may be viewed as a tax incentive, an escrow account, or a loan to the government according to the particular arrangement that is finally worked out. We add to this the interestingly visible incentive initiated by France in 1976 whereby industrial consumers received a credit of \$13 (in the form of reduced taxes) for every barrel of oil saved.

*The economic return on such projects is rarely sufficient to excite anyone. In fact, some companies have found it more economic to retire their cogeneration units in selected facilities because of the relatively low cost of locally purchased electricity.

TABLE 4.1
PAPER COMPANIES AND TRADE ORGANIZATIONS SURVEYED

- **Paper Companies**

- Boise Cascade Corporation
- Champion International
- Crown Zellerbach
- Erving Paper Mills Company
- International Paper Company
- Mead Corporation
- Potlatch Corporation
- Westvaco Corporation
- Weyerhaeuser Company

- **Trade Organizations**

- American Paper Institute
- TAPPI:
 - Energy Committee
 - Research and Development Subcommittee

Current air quality regulations were consistently viewed as the chief disincentive to the increased use of coal- and wood-fired boilers, and these are essential if the industry is to fulfill its commitment to move away from its known substantial reliance on residual fuel oil.* Some industry leaders believe that energy self-sufficiency might ultimately become possible with wood wastes. One proposal advanced to alleviate the problem was to base the regulations on total or ambient effluents rather than on effluents from point sources. (This so-called "bubble" policy has since been adopted by the EPA.) The second suggestion, however, that pollutants should be measured in terms of annual rates instead of hourly rates may be less defensible for health reasons.

Another area of activity and great interest is the potential closing of integrated mills to minimize or completely internalize all polluting fluid effluents. Research and development in this field is intimately connected with the development of new pulping chemicals and technologies, such as anthraquinone and continuous pulping. There are serious problems, however, as were revealed in the Canadian installation in Thunder Bay, Ontario. The problems are related to corrosion, the build-up of chemicals, instabilities, and automatic process loop control.

4.2 PROMISING ENERGY CONSERVING TECHNOLOGIES FOR PAPER FORMING

While it was generally maintained that the industry is able to satisfy its requirements for research and development in its own facilities or through industrial grants to various institutions, the role of the DOE as a partner in risk was recognized as being a useful one in accelerating the introduction of novel technologies.

*The total 1978 gross energy requirements of the industry amounted to somewhat more than 900,000 equivalent barrels of oil per day. Hence, a one percentage point increase in the use of wastes would result in fuel oil savings of about 9000 real barrels per day.

A review of the responses to our survey showed that the fundable projects of greatest common interest could appropriately be grouped in three categories: (1) studies of energy use and management, (2) modest advancement of current technologies, and (3) fundamental changes in papermaking technology.

Because of the complicated manner in which energy is used in a mill, it is usually very difficult, if not impossible, to trace all energy sources and sinks. Architect/engineers serving the industry are increasingly being asked to conduct energy audits. The results, however, are generally ambiguous because of the cascaded way that energy is distributed among the different processes and the complicated manner in which the processes themselves interact with each other. Hence, any benefits resulting from the improved use of energy in one process could be mitigated by the consequences to another process in the chain. In other words, energy management in a mill is a systems problem. Still, there is much room for improvement, but it is necessary to develop energy audit methodologies that are specifically tailored to the industry. The benefits of increased process automation and control were also recognized and recommended for investigation.* Another suggestion was to prepare a compendium of the energy saving technologies currently in the marketplace and the energy benefits that can be achieved when these technologies are used in various configurations. Such a study was sponsored by the Swedish government some time ago.

The second category of projects consists primarily of improvements in dryer section technology, press section optimization, and the development of inexpensive heat exchangers. The third category dealing with fundamental changes in process technology includes high consistency forming and dry forming. These items are discussed in the following program plan.

*Such a study was recently undertaken for the DOE and concluded that 0.2 quads of energy could be saved with computer process control. See Fam, S., "Impact on Energy Conservation of Automatic Control Systems Utilization in the U.S. Pulp and Paper Industry," July 1979.

5. A PROGRAM PLAN FOR RD&D OF ENERGY CONSERVING TECHNOLOGIES FOR PAPERMAKING

The program plan presented in this section is the result of numerous consultations and personal interviews and correspondence over a period of 10 months* with leading representatives from the papermaking industry, equipment manufacturers, engineering consulting firms, the API Energy Committee, and individual members of the TAPPI Research and Development Subcommittee. The plan also takes into account the R&D recommendations made by the industry in previous energy workshops sponsored by the DOE, and the projects underway during the period of investigation or being reviewed for possible funding.

5.1 SCOPE AND PURPOSE OF THE PROGRAM PLAN

The program plan focuses primarily on the industry's near term needs for research, development, and demonstration of energy conserving technologies and process innovations in papermaking operations downstream of the pulping process (i.e., stock preparation, web formation, pressing and drying).

The purpose of the plan is to provide the DOE with a broadly supported program that will enable it to successfully pursue its energy conservation efforts in partnership with industry. We believe that this purpose is best served by providing somewhat tighter direction than can be obtained from watered down versions enjoying the widest consensus. Consequently, the program plan is structured to illuminate those major areas where important energy savings could be achieved in the near term, and to provide a framework for the longer term development of potentially more energy-efficient forming technologies.

The program is divided into 3 sections:

*March 1978 to December 1978

- Energy Use and Management
- Modest Advancement of Current Technology
- Fundamental Changes in Forming Technology

5.2 ENERGY USE AND MANAGEMENT

5.2.1 Energy Management System Study

Over 70 percent of all the grades of paper and paperboard in the U.S. are produced in integrated mills. Thus, the pattern of energy use in papermaking is seldom independent of the upstream pulping operations, and any significant change in the energy use of a unit papermaking process is likely to be reflected elsewhere in the chain. The problem of optimizing the energy distribution and management in most of the paper and board mills is therefore a systems problem about which no adequate treatment exists. Such a treatment would provide a methodology for energy auditing and would be useful in ascertaining to what extent the potential for fuel savings in one operation could be mitigated by modifications made to another operation.

The objective of the energy management system study is to devise methods of optimizing the management and distribution of energy in integrated mills. The study would include: data gathering, analysis, and modeling of typical patterns of energy use; a system investigation of the interactions of the major unit operations; the development of a methodology for energy auditing; and recommendations for the optimization of energy use throughout the entire mill.

5.2.2 System Automation Studies

The DOE is currently considering a number of proposals for the application of automatic process control in the pulp and paper industry. A recently completed study (see footnote p. 24) concluded that substantial savings could be achieved in the pulping and recovery operations with computer control and that the lack of appropriate sensor technology and

supporting systems software were serious roadblocks. In line with these findings, we propose that further work be directed at identifying the proper process control parameters, developing the sensors required to measure them, and producing the software linkage to complete the automation loop. The ultimate purpose of this work is to incorporate the remaining nonautomated processes into a working network in a demonstration plant.

5.2.3 Comparison Study of Alternate Available Technologies

A compilation of available fuel-conserving technologies and their applications in the pulp and paper industry was recently completed under the auspices of the Swedish government. A similar study for the U.S. industry would be well received by the industrial community as a useful guide to the vast array of equipment currently in the market place. We view this study as a lower priority effort than either of the above studies.

5.3 MODEST ADVANCEMENT OF CURRENT TECHNOLOGY

5.3.1 Dryer Section Technology

Most of the energy in the fuels consumed for papermaking is rejected into the atmosphere during the drying operating in the form of a low temperature mixture of air and water vapor. In most cases, the economic recovery and subsequent reuse of the water vapor is not currently feasible in this country because of the difficulty of economically separating the vapor from the air. Recovering part of the heat indirectly by heat exchange is also not economical because of the large exchange surfaces that are required.

The pursuit of mill management practices for steam conservation in the dryer section has led to significant improvements in total and specific steam consumption. Rates of 1.5 pounds of steam per pound of moisture evaporated can be realized. Further reduction below this value is unlikely to be significant as the mass and heat transfer processes involved provide a physical limit. A more fundamental approach is required to progress here.

Instead of using heated solid surfaces and moving air for evaporative drying, consideration should be given to other forms of fluid cycles under the general heading of airless drying. There are many fundamental questions to be answered in this area as well as significant problems of practical implementation.

Our RD&D program calls for a three-pronged technological approach to these situations:

1. Develop and implement technology for low-temperature heat utilization, such as inexpensive "plastic" heat exchangers, which will permit the economic recovery of a substantial portion of the rejected heat using current dryer technology.
2. Develop airless dryers which will obviate the need for air/vapor separation and thus permit the economic recovery of the low-temperature vapor.
3. Encourage the development of papermaking technology along a direction that substantially reduces the drying requirement (i.e. high consistency forming), or eliminates it completely (i.e. dry forming).

These projects are discussed in Sections 5.3.2 and 5.4 respectively.

5.3.2 Development of Inexpensive Heat Exchangers

The DOE is currently sponsoring the development of a hybrid, inexpensive nonfouling heat exchanger for a diesel heat recovery application. The heat exchanger in this study, which is funded by the Fossil Energy Department, consists of a metallic hot section and a low temperature "plastic" section. The project is not expected to progress beyond the study stage. We propose that the program be continued for conservation applications with a change in emphasis to the design, experimental development, and demonstration of an all-plastic exchanger. Such a heat exchanger would also be useful in the food and textile industries.

5.3.3 Press Section Optimization

The potential for energy savings in the press section is large in theory. This results from the fact that a 4- to 6-percent reduction in dryer section steam consumption will be produced by a 1-percent increase in dryness out of the press section. The large advantage to be gained from increased dryness out of the press section holds over a wide range of exit dryness values.

The performance of the press is a function of such design factors as press and nip geometry, roll cover design, and felt runs and type. It also depends on operating conditions such as machine speed, loading, felt cleaning and conditioning, suction level and water removal. A further range of contributing factors are associated with the stock, viz: such factors as basis weight, filler content, freeness, fiber type, temperature, sheet wetness at entry, table drainage and formation history. Published data, such as those on the effect of an extended nip region, indicate that further improvements in dryness are indeed possible. Suggested work areas for DOE support are:

1. Press modeling to extend the current understanding of the mechanism so that ranges of applicability of new pressing methods can be determined.
2. Methods for significantly improving press dryness with an assessment of associated changes in drive and vacuum power requirements.
3. The role of felt conditioning in press section water removal.

DOE already has some ongoing programs in these areas with the University of Maine's work on press modeling, and the Georgia Technical University's investigation of the use of the mach nozzle for felt drying.

5.3.4 Stock Delivery and Forming Section

Although most of the energy in papermaking is used in the drying stage, a significant amount of power is required for the refiner, fan pump, wire drive, and drainage vacuum system. No specific programs of work are

proposed in this plan, but it should be recognized that there are opportunities for energy saving in these areas. Hence, appropriate work aimed at a better understanding of these components of the paper machine should be considered sympathetically.

5.4 FUNDAMENTAL CHANGES IN FORMING TECHNOLOGY

5.4.1 High Consistency Forming

The industry's public view of high consistency forming is skeptical, or at best ambivalent. The technical literature, however, suggests that this attitude is by no means uniform as paper companies, equipment manufacturers, and private researchers continue to explore the realizable possibilities of this technology.

It is now well established that sheets or board formed at high consistency have significantly different physical properties, particularly in having lower machine direction strength. This is attributed to the higher proportion of fiber having significant Z-direction orientation. It is felt that the products suitable for high consistency forming are those in which strength is not of prime importance such as pulp, corrugating medium and filler plys for multi-ply board. These products represent a significant proportion of the paper industry production because of the high sheet basis weight. It also follows that the total energy saving potential is significant provided the published data on improved pressing and drying efficiencies can be achieved for all grades and operating conditions. The published data remain small.

The mechanisms by which energy consumption might be reduced are:

1. Stock Supply and Water Recirculation

Fan pump power will be reduced because of the large reduction in stock and water volume flow rates. However, this is offset by the increased pressure drop and energy consumption in the head-box required for flock breaking at high consistency. The frictional

resistance of the stock flow will be different at the high consistency so that new design criteria are required for the approach piping used to deliver the stock to the headbox. The net balance of total energy consumption is not established and requires further study.

2. Reduction of Fourdrinier Drive Power

High consistency forming will allow shorter table lengths for comparable production rates and possible reduction of drive power because of the reduced number of drainage or wire support elements.

3. Improved Pressing Efficiency

Published data are small, but dryness out of the press section can be increased by 1 to 3 percent.

4. Improved Drying Efficiency

Published data suggest a possible reduction in drying energy consumption of about 15 percent.

The total energy saving potential from these mechanisms may be as high as 25 percent. We propose that work be supported by DOE in this area to determine the interaction between product quality and energy savings.

5.4.2 Dry Forming

This is a tightly guarded technology marked by strong proprietary interests and vigorous litigation. There is some question as to whether dry forming will ultimately offer net energy savings, as well as concerns about paper quality and fire and other health hazards. Nevertheless, there are real benefits to be derived and the technology is moving forward.

In view of the legal situation, we do not see a clearly definable role for the DOE at this time. Our recommendation is to keep abreast of the technological and legal developments with a view of determining the appropriate support to provide in the future.

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DOE Contract No. DE-AC02-78CS40150
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HIGH CONSISTENCY FORMING
PROCESS FOR PAPERMAKING
PART II FINAL REPORT

by

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LODDING REPORT LR-108

April, 1980

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SUMMARY

The main aim of this contract is to demonstrate the energy savings that can be achieved by the high consistency forming of paper and board. In Phase I, consideration was also given to papermaking test facilities. The case for a centralized test facility is discussed. The results of a survey of existing pilot paper machines are presented. The energy saving potential of high consistency forming is considered and related to existing evidence. Simple theoretical models for the press nip action and the drying process are developed to predict where high consistency forming will reduce energy consumption. A special dynamic former has been designed, fabricated and commissioned to allow development of a laboratory high consistency headbox. The design and construction of a low speed headbox has been completed and the complete system operated. Special equipment and techniques for the measurement of the water and air permeability of sheet samples have been developed.

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2. INTRODUCTION

This report describes progress on Phase I of a contract whose prime purpose is to demonstrate and quantify the energy saving potential in forming paper and board products at stock consistencies in the range 2 to 4%. The properties and features of such high consistency forming were investigated in three ways:

- a) Analysis and modeling of the drainage, pressing and drying processes to determine the magnitude of effects.
- b) Review of available evidence on energy saving.
- c) Continued experimental work on the formation process and the measurement of physical and hydrodynamic properties of sample sheets in comparison with those formed as hand sheets at conventional low consistencies. This work builds on the previous Lodding experience in high consistency forming using laboratory facilities and field installations.

The potential for energy saving in high consistency forming arises from the nature of the fiber orientation in the sheet. The sheet has a more felted structure instead of layered and is more permeable to both water and air flow. This results in easier drainage, more water removal in pressing and a higher evaporation rate in the dryer section. The evidence to support this hypothesis is limited and an important contract requirement is to produce substantial and reliable data to substantiate or invalidate the hypothesis before a full-scale mill demonstration program is undertaken. The other physical properties of the sheet such as strength, tear, bulk, formation uniformity, etc. are also important in determining the

particular markets for products formed at high stock consistency. Some of these properties are to be correlated with the increased energy saving as part of the contract program.

Lodging experience with high consistency headbox testing on production paper and board machines had shown problems in experimental control and lack of flexibility in changing headbox parameters. The design philosophy that had been adopted required a relatively high machine speed (in excess of 1000 ft./min.) in order to generate the levels of floc breaking energy required for stock consistencies in the 2 to 4% range. The availability of pilot paper machines to facilitate development work was found to be extremely limited. It was, therefore, proposed to pursue the establishment of a centralized test facility centered on a sophisticated high speed paper machine, so that technology such as high consistency forming could proceed more effectively. In order to investigate the case for such a facility, further tasks were undertaken under Phase I of the contract. A comprehensive survey of the major specifications and availability of existing pilot paper machines within the U.S. was undertaken. The results are presented in Section 3.0 of this report. A study to complete the specifications, preliminary design and costing of the facility was carried out in conjunction with consulting engineers of the C.T. Main Company in Boston, Massachusetts. The results are also presented in Section 3. and Appendix II. A research, development and demonstration program plan for paper forming was prepared by the Energy Systems Division of Thermo Electron at its Waltham Center in Massachusetts, following an extensive survey of industry representatives and organizations. The results are to be presented separately, but some of the conclusions are incorporated in Section 3.1 where the case for the

centralized facility is discussed. The detailed work statement for Phase I of the contract is presented in Appendix I.

In an attempt to provide some preliminary information on energy saving with paper formed at high consistency, an attempt was made to form handsheets at a range of consistencies from 0.05% to 3%. The sheets were compared on the basis of static pressing to equilibrium, tensile, strength and formation. These studies suggested that the felted structure associated with high consistency forming was not achieved with the handsheet technique, although no theoretical basis could be formulated for this result. Equally important, a quality of formation for the high consistency sheets equivalent to that of the low consistency sheets could not be achieved by the conventional handsheet forming method because of the impracticalities of introducing sufficient floc breaking turbulence into the very small stock volume. A number of techniques for overcoming this difficulty were considered and conceptual designs produced. However, they all involved some form of dynamic action with varying degrees of mechanical and hydrodynamic complexity. The simplest and most useful embodiment of such a "dynamic former" was judged to be a moving wire section of fourdrinier type, although greatly reduced in length, with stock delivery through a special headbox. The decision to proceed with this type of test equipment represented a deviation from the original contract program but did not change the tasks or aims. A no-cost extension to the contract was negotiated with the Department of Energy to accommodate the extra time required to design, fabricate and commission the dynamic former. The contract programs for high consistency forming as originally proposed and currently in effect are compared in figure 2.1. Some advantages arise from the revised

program and work schedule:

- a) Headbox development work can continue readily.
- b) The work is not dependent on the implementation of a centralized test facility, but can proceed using equipment developed specifically for the high consistency forming on an ad hoc basis.
- c) The overall program time scale is significantly shorter and less costly.
- d) An intermediate decision point is introduced into the program whereby the energy saving potential can be assessed before moving to an extensive headbox development stage and the full scale mill implementation.

As detailed in Section 7.2 , the choice of 400 ft./min. for the operating speed of the dynamic former was a compromise between a large stock storage facility and adequate run time to establish equilibrium and permit the required changes in test operating conditions. This choice of relatively low speed meant that part of the Phase I program was devoted to the development of a special headbox to perform at this speed, which is significantly below the operating range of the existing Lodding design.

The work described in this Phase I final report was carried out under Department of Energy contract number EM-78-C-02-4611 in the period from February 1, 1978 to May 31, 1979.

Figure 2.1 Comparison of Contract Programs as Originally Proposed and as Currently in Effect

3. PILOT MACHINES FOR PAPERMAKING STUDIES

A mixture of laboratory facilities and production machines had been used in the development of high consistency headboxes at Lodding, with a corresponding mixture of experiences. Laboratory facilities were generally adequate for the investigation of hydraulic elements of the headboxes. There was a limited availability of pilot paper machines for controlled experimentation with complete headbox designs, particularly at the high machine speeds which were felt to be necessary for the high consistency forming application. Tests on full-scale production machines were found to be expensive and not very flexible for the control and variation of the experimental parameters. Against this background and as part of Phase I of the contract, studies and surveys were carried out with the following aims:

- 1) To investigate the case for a centralized pilot machine facility.
- 2) To survey the current disposition and availability of existing pilot machines within the U.S.
- 3) To investigate the possibility of adaptating an existing pilot machine for high consistency forming or the design and fabrication of a special purpose dynamic former comprising moving wire section and assorted drainage devices.

3.1 The Centralized Test Facility, Design Specifications and Cost

In Europe and Canada, there is a larger concentration of research facilities for the pulp and paper industry than in the U.S. This comes close to the ultimate with the new high speed, multi-configuration, multi-million dollar paper machine to be built at the Swedish Forest Products Research Institute in Stockholm with joint government and private industry funding. In the U.S. aerospace industry, centralized test facilities, such as wind tunnels, are accepted and provide a useful function. They are, of course, necessary for support of defense and military development work as well as commercial aircraft projects. The case for a centralized test facility for the pulp and paper industry was considered from the points of view of function, advantages and disadvantages, design, costs and availability of other facilities. Industry opinions were surveyed in conjunction with another contract task (the formulation of a research, development and demonstration program for energy conservation in paper technology), which is to be reported separately.

The functions of a pilot paper machine can be identified as:

- 1) Development of new and improved paper products.

Most large paper companies currently devote the majority of their research effort in this area and have sophisticated in-house machines and facilities to support the activity. With very few exceptions, these facilities are in constant use, have an extensive back-log of work and are unavailable for external users. Manufacturing techniques for some paper products, such as tissue, are extremely proprietary which justifies the specialized in-house facilities.

2) New basic papermaking technology.

This is a relatively small part of papermaking research and involves such aspects as high consistency forming and dry forming. A centralized test facility would aid this type of project and its location would be important from accessibility and organizational points of view. However, most of this technology can be advanced on an ad hoc laboratory and field test basis using existing facilities.

3) Development of machines and accessory equipment.

Pilot and full scale machines are required for much of this function, but the development work is usually of a proprietary nature and not suited to a centralized facility. The machine builders and larger accessory suppliers have in-house pilot facilities for their particular needs.

4) Marketing demonstration of machines.

This is a commercial function of the pilot facility, whereby the operation and product quality can be demonstrated to potential customers. A centralized facility would have little or no direct participation in this process.

5) Teaching and process demonstration.

An important function of many of the existing pilot machines is teaching and demonstration of the paper making process. Pilot machines performing this function are typically located at universities and tend to be very slow, having limited use as research facilities. A centralized facility would provide a demonstration with machine speeds more representative of present industry practice. However,

it would not be convenient for university students to use it.

A design study was carried out in 1977 by C. T. Main, for the Lodging Division of Thermo Electron Corporation. The first stage consisted of the fourdrinier machine with associated low consistency stock preparation and delivery system, a two nip press section and wind-up or reeling device. The original specification required a maximum capability in machine speed of 4000 ft/min., a wire width of 24 inches and a table length of 30 ft. The design operating condition was a 15 minute run time at 2000 ft/min. machine speed and sheet basis weight of 40 lb./1000 sq. ft. In Phase I of the contract, this design was updated by C. T. Main and a further study made of the specifications for an added dryer section and the modification of the fourdrinier section to incorporate an alternate twin wire configuration. Several dryer section configurations were considered, but only two were estimated for cost because they were regarded as being the most practical. The first (Alternate A) was a full dryer section. The second (Alternate C) comprised a partial on-line dryer section with a wind-up/unwind device which could then be used for subsequent sheet re-runs through the dryers either at full machine speed or at a lower speed. The details and discussions from the two C. T. Main study reports are outlined in Appendix II, which also includes a layout drawing for the machine and facility. The cost estimates include building, auxiliary plant and stock preparation equipment costs. Also included in Appendix II, is an outline of the instrumentation and the quantities that must be measured in order to monitor the energy saving technology.

The cost estimates for the pilot machine can be summarized from the detailed breakdown in Appendix II as:

Fourdrinier pilot machine with building,	
stock preparation and plant equipment	\$2,025,000
Additional twin-wire configuration	245,000
Additional dryer section (Alternate A, full section)	4,975,000
Additional dryer section (Alternate C, partial section)	1,316,000
	<hr/>
Total cost with alternate C dryer Section	<u>\$3,586,000</u>

To justify the high capital cost for such a facility would require an extensive, continuous and continuing work program, and a sound organization to ensure effective and economic usage. An analysis of the staffing requirements and running costs show that the annual operating cost would be in the region of \$500,000 to \$700,000. An estimated customer charge of \$2,500 to \$3,000 per day would be necessary.

The capital and operating costs of such a pilot machine would be modified if it were to be located in conjunction with an existing facility. Many possibilities exist such as the conversion of an existing mill site or an addition at establishments such as the U.S. Department of Agriculture at Peoria, the National Bureau of Standards, the Institute of Paper Chemistry and the various Universities with paper technology courses and research programs. The survey of

existing pilot machines described in detail in Section 3.2 of this report shows that there is no high speed fourdrinier machine in the U.S. with reasonable availability to any user.

The case for and against a centralized test facility can be summarized under the following advantages and disadvantages:

ADVANTAGES

- 1) Good control of test parameters, variables and measurements.
- 2) Flexibility for basic technology research and development.
- 3) Resources, equipment and manpower can be concentrated.
- 4) No advanced independent facility of this kind currently exists in the U.S.

DISADVANTAGES

- 1) Pilot paper machine simulation is not accurate for all products.
- 2) High capital cost and investment.
- 3) Expensive, large-scale operation.
- 4) Technology can be advanced by ad hoc testing in existing facilities.
- 5) Difficult organizational, control and responsibility situation because of (a) proprietary and commercial interests and (b) the broad range of industry research and development requirements.
- 6) The difficulty of ensuring an adequate operational income.

Opinions surveyed in the industry suggest that a centralized test facility would be attractive from a purely technical point of view although the pros and cons are balanced. However, the U.S. paper industry is decentralized (if regionalized) geographically and is independent in attitude. Cooperation and information exchanges come through mutual interest. In surveying current and future research and development, no new technology is perceived whose progress is halted or seriously delayed through the lack of a centralized test facility. Where such a facility might be of interest to the industry and the U.S. Department of Energy is in the demonstration of technology which has significant energy saving potential, but a poor return on investment. With the current energy cost increasing, the need for such demonstrations is reducing because returns are no longer poor. The recommendation from this study, therefore, is that such a major centralized test facility should have no priority for Department of Energy support at this time.

3.2 Pilot Paper Machine Survey

As part of Phase I of the contract, a survey of the current disposition and availability of existing pilot paper machines within the United States was carried out. The initial survey was conducted by telephone. Subsequently a written summary of the telephone survey data obtained from each institution was submitted to the appropriate contact at the institution for verification and permission to publish. Although this has been a lengthy process, the final survey is believed to be the most compressive pilot machine survey taken within the United States.

Permission was received to publish data regarding 41 test machines. A complete listing of the verified data is given in Appendix III. The breakdown of machines by institution is as follows:

- 4 Machines in Independent Foundations - All four are located at the Herty Foundation. They are complete machines operating at or below 300 fpm.
- 4 Machines in U.S. Government Centers - All complete machines of which the fastest is capable of 500 fpm.
- 12 Machines in Universities - Typically very low speed, under 200 fpm, machines with press sections and occasionally dryers. They are used primarily for educational purposes. Two notable exceptions are a 900 fpm cylinder former at the University of Western Michigan and 1000 fpm fourdrinier at the Institute of Paper Chemistry.
- 13 Machines in Paper Companies - Five of these are owned by companies which manufacture tissue paper and related products. This industry is so competitive that all information regarding these machines is proprietary.

The Westvaco Corporation is the only paper Company which admits to owning a machine capable of speeds in excess of 250 fpm, and they are so busy with corporate use that the machine is not available.

- 8 Machines in Equipment Supplier Plants - These are by far the most interesting for high consistency work as four of them are capable of speeds in excess of 2000 fpm. Although all four are equipped with press sections, none have dryers.

The distribution of pilot paper machines by speed (for the 36 machines reporting operating ranges) is shown in Figure 3.1. A distinction is made between fourdrinier and other types of machines as it will be easier to conduct tests on, and make retrofits to, fourdrinier machines. "Other" includes twin wire, cylinder and Webster type formers.

The goal of the survey was to collect and disseminate information on the pilot paper machines in such a way that their respective strengths and weaknesses would be readily apparent. The initial telephone survey was quite detailed as indicated by the sample sheet in Appendix III. Once this data had been collected, it became apparent that there was too much detail to make meaningful comparisons between the wide range of machines surveyed. The categories set forth in the verified survey in Appendix III were chosen as the most useful.

An initial interest was whether an institution would consider the possibility of using the machine for Lodding high consistency research and development projects. This was the question asked in the telephone survey. In the process of defining the categories for the verified survey, it was decided that a more appropriate question would be

whether the pilot machine was generally available to any user, irrespective of affiliation.

The definition of general availability of the pilot facilities has been the most difficult part of the study. Different organizations have different guidelines governing who can use the facility depending on commercial and proprietary constraints. Some have very specific policies, while others are less clearly defined. Rather than attempt to categorize these, we have, for summary purposes, differentiated between those facilities with limitations on user category and those with no restrictions other than time scheduling. Unfortunately, this can be misleading when the general policy is for general availability, but there is no time available.

In most cases, the change in emphasis on machine availability was not significant. However, it led to some confusion and, in several cases, the responses were changed. During the one and a half years over which this survey was conducted, policies of some of the institutions clearly changed, one machine became inoperative, and one owned by Mead Corp. is now unavailable and was removed from the survey. This indicates that the status of these test machines is constantly in flux. The results presented in Appendix III are a summary of the status in 1979.

Figure 3.2 shows the distribution of pilot paper machines with reasonable availability to outside users. The next section, 3.3, describes the results of the search for a suitable fourdrinier pilot machine for high consistency forming work.

3.3 Investigation of Pilot Paper Machines Suitable for High Consistency Forming

Lodding's major emphasis has been on high consistency headbox design for fourdrinier machines. These tend to be older machines and many need to be rebuilt to remain cost effective. An ideal time to convert to high consistency forming would be during such a rebuild. The fourdrinier geometry also lends itself well to the formation of multiple sheets where high consistency forming may be beneficial. The fourdrinier is also preferred for testing purposes because the prototype configurations can usually be placed on the table without moving the conventional low consistency headbox.

Several of the promising pilot machines were investigated at the beginning of Phase I to determine if they could be used to form the high consistency sheets required for the contract work. Examination of figures 3.1 and 3.2 would lead one to believe there are several fourdrinier test machines available for high consistency work, however:

- 1) Huyck (Equipment Supplier) has a high speed fourdrinier which they asked us to put in the available for outside use category. Unfortunately, in discussion with their Mr. Fredrick Smart, it was revealed that their internal scheduling requirements were so tight that there was only a slim chance that Lodding could obtain testing time.
- 2) The Institute of Paper Chemistry (Universities) has a 1000 fpm machine which is listed in the available category. Unfortunately, their Mr. T.S.Fox

indicated that it has not run in several years. During earlier contacts with the Institute, they said the drive and table configuration would only be capable of making a light grade sheet like newsprint at 1000 fpm. Furthermore, no presses or dryers are available.

- 3) The University of Western Michigan (Universities) has a similar problem. Their 900 fpm cylinder former will only run at 400-500 fpm for the linerboard grades in which we are interested. It was donated to the institute and has only been run a few times. Their fourdrinier operates in the 200 fpm speed range.
- 4) Neither of the Sandy Hill machines are conventional fourdriniers, and although they have run up to 1000 fpm on tissue, typical operating speeds are below 500 fpm.
- 5) The U.S. Department of Agriculture (U.S. Government Facilities) cannot exceed 200 fpm with linerboard grades without crushing in the press section and incomplete drying in the dryers.

Of the pilot machines mentioned above, the Government facility is one of the most interesting, partially because of Dr. Hofreiter's enthusiasm for a cooperative venture, and partially because it is a machine which is used on a regular basis. A prototype high consistency headbox could easily be mounted on the machine frame following the headbox and comparisons could be made between high

and low consistency sheets dynamically formed from the same stock.

The operating speed presents the major difficulty. At the conclusion of Phase II, the headbox and pressing trials will indicate whether a meaningful machine trial can be conducted at speeds below 500 fpm. In any event, this facility could be used to form high and low consistency sheets dynamically, even if they had to be collected at the couch roll with subsequent off machine pressing.

The possibility of doing comparison studies on the dryer section at the U.S. Department of Agriculture was also investigated. There is no equipment for monitoring steam flow rates to the dryers, although the condensate return flow rate can be monitored as an indication of the steam usage. This was done for several runs, and the results were not repeatable on a day to day basis. As there is considerably more dryer drum area exposed to the surrounding air than in contact with the sheet, it is assumed that daily fluctuations in the ambient temperature and humidity were influencing the results. A more detailed study will be required to determine if any small width dryer can be controlled to the extent required for comparison drying rate studies.

A series of design concepts for producing high consistency sheets without a pilot machine were investigated, and the results are presented in sections 7.1 and 7.2. The final decision was to manufacture the dynamic former described in section 7.3 and develop a low speed headbox design for use on the dynamic former. The headbox work is covered in section 7.4.

Although this represented a deviation from the original contract program, it also allowed the overall program to be completed in less

time and at lower cost. The major factor which allows this is a decoupling of the various sections of the machine. By forming the sheets independently of both the pressing and drying, there is considerably more control over the important controlling variables in each section. The scaling laws for the press section developed in section 5 of this report, allow the simulation of high speed pressing with a relatively small scale dynamic press. By conducting the tests on this small scale ad hoc basis, more detailed information will be obtained at a lower cost.

Figure 3.1. Distribution of Pilot Paper Machines by Speed
(Irrespective of Availability)

Figure 3.2. Distribution of Pilot Paper Machines by Speed
(with Reasonable Availability)

4. HIGH CONSISTENCY FORMING AND ENERGY SAVING POTENTIAL

4.1. General Considerations

The breakdown of energy consumption by machine section for the paper and board making process is well established. The detailed figures depend on many factors such as type of product, machine speed and wet end configuration. However, some typical figures for fourdrinier machines are summarized in the following table.

The numbers (horsepower days/ton of paper) are broken down by machine function and grade of paper.

MACHINE FUNCTION	GRADE OF PAPER		
	<u>Newsprint</u>	<u>Fine Paper</u>	<u>Linerboard</u>
Refining	1.1	3.4	9.5
Fan pump	1.7	1.0	1.1
Table drive	1.6	1.0	2.3
Table vacuum	1.0	1.5	1.1
Press drive	3.3	2.0	2.0
Press vacuum	4.0	5.0	4.0
Dryer drive	<u>1.8</u>	<u>1.5</u>	<u>2.0</u>
<u>Total Mechanical</u>	<u>14.5</u>	<u>15.4</u>	<u>22.0</u>
Dryer thermal energy	60	60	67
$(3.7 \times 10^6 \text{ BTU/ton})(3.7 \times 10^6 \text{ BTU/ton})(4.1 \times 10^6 \text{ BTU/ton})$			

The dryer thermal consumption is by far the largest single item and usually accounts for 70 to 80% of the total energy. The figures in the table can be regarded as specific energy consumptions and can be used as comparative measures of the energy efficiency for water removal in the various stages of papermaking. The broad aims of new technology aimed towards conservation should be:

1. Reduce the specific energy consumption for the process.
2. Remove more water in those processes which have the lowest specific consumptions, i.e. reduce the amount of water removed in the dryer by increasing the amount removed in the press and table sections.

High consistency forming is directed towards both these aims.

To aid in the assessment of proposed technologies and to assess the sensitivity to changes in machine conditions, simplified lumped parameter models which incorporate trends indicated by theories for table drainage, press, and dryer action were developed. These models are in part supported or based on empirical and measured data such as sheet porosities and consistency distributions down the length of the paper machine. Conceptually a total machine model could be developed by sectionalizing the components of machine operation as follows:

1. Gravity drainage.
2. Foil or table roll action.
3. Table suction.
4. Couch suction.
5. Press action.
6. Drying process.

Typical sheet consistencies at the end of each section and at key points within these sections are known or can be inferred from on machine measurements. The rate of water removal in each section of the machine can then be determined knowing the production rate and typical sheet consistencies at the beginning and end of the section.

Empirical or theoretical knowledge of the variables controlling water removal in each section can be used to assess the sensitivity to changes in these variables.

Relatively detailed models of the sensitivity of the water removal in the press and dryer sections to changes in physical variables and operating parameters are presented in sections 5 and 6 respectively. These models were developed from the extensive body of literature regarding these two sections of the paper machine. It is interesting to note that the amount of published information on research regarding water removal in the press section reflects a general understanding by the paper industry that maximizing water removal in the press section will minimize overall energy consumption.

Conversely, while there is a fairly large body of literature on table drainage concerning the region when the sheet is saturated with water (papermachine sections 1 and 2 above), there is very little literature with regard to vacuum induced drainage (papermachine sections 3 and 4 above). This may be because vacuum induced drainage is believed to be more complex than the other sections of the paper machine as there is a two phase flow of air and water in this section. However, recent work indicates that two phase flows are equally important in the press section (Reference 1). Presumably the lack of published data is also due to the conclusion (to be emphasized in section 4.3) that the major energy savings can be achieved most directly by maximizing water removal in the press section. In the next section, 4.2, a generalized discussion of the potential energy savings from high consistency forming for the paper machine segments ahead of the press section is presented. These arguments are not as detailed

as those for the press and dryer section because there is less information available.

4.2 Wet End Energy Balances

The potential for saving energy through high consistency forming can be sought in the following two areas ahead of the press section.

A. Reduced wet end water circulation.

1. Lower pumping power
2. Reduced thermal losses.
3. Lower mechanical drive power for the table.

B. Increased web permeability.

1. Improved table drainage.
2. Lower table vacuum power.

The function of the fan pump is to generate the pressure head necessary for the following.

1. To raise the stock to headbox level (i.e. overcome the gravity head).
2. To accelerate the stock to the table speed.
3. To overcome supply piping friction losses.
4. To provide the headbox turbulence for floc breaking and stock uniformity.

The pressure difference required for 1 and 2 is independent of stock consistency. The associated fan pump power consumption is given by the product of this pressure difference and the volume flow rate. Since flow rate is inversely proportional to consistency, the pump power

for 1. and 2. decreases with increasing headbox consistency.

The pressure difference required for 3. and 4. is a sensitive function of consistency and can increase rapidly with consistency at some flow velocities and pipe diameters. Under some conditions, the required pressure difference increases with the third or fourth power of the consistency. Therefore, although the volume flow rate is reducing, the fan pump power for items 3. and 4. may be increasing as the square or cube of the consistency.

The total pump power for all the items 1. through 4., therefore, consists of one part which reduces with consistency and a second part which increases rapidly with consistency. The balance between these two terms is a function of the particular machine installation and supply piping layout. It is difficult to draw general conclusions except that the design of the approach system for stock delivery will be even more critical for high consistency than it is for low consistency.

Table drive power for high consistency forming will be significantly less because the table is much shorter. Most of the frictional elements such as table rolls and foils on the forming section of a conventional fourdrinier type paper machine can be eliminated because the stock from a high consistency headbox contains much less water when it meets the wire. It is assumed that the increased web permeability of a high consistency sheet will result in a reduction of the vacuum levels required in the vacuum induced drainage devices, such as the suction boxes and couch rolls. These reduced vacuum levels will result in a corresponding reduction in the frictional drag produced by the suction boxes and the required drive power.

This reduction in vacuum level will also result in a lower energy requirement for the wet end vacuum pumps.

Most paper machines operate with stock temperatures which are significantly higher than the surrounding ambient temperature. Thermal energy savings are expected from high consistency forming due to the reduced surface area of the wet end piping required for the lower flow rates associated with high consistency forming. The water removal balances for the machine are compared for high and low consistency forming in figure 4.1. The low consistency figures are enclosed in the curved parentheses while the corresponding high consistency values are in square parentheses.

Typically, about 30 gal/min. of white water are drained from the forming table and recirculated to dilute the incoming thick stock for each ton of paper produced per day using a conventional headbox. The corresponding figure is 5 gal/min. for high consistency forming. Therefore, assuming heat loss is proportional to volume flow rate, any thermal losses from the white water will be reduced about 70% with a high consistency layout. Flow rates, and therefore, thermal energy consumption are expected to be similar for the thick stock flows before white water dilution with both high and low consistency forming.

4.3 Energy Saving Potential

As discussed in the previous section, 4.2, energy savings due to high consistency forming on a fourdrinier type table configuration will be due to reductions in drive power and vacuum power requirements

as well as thermal losses. No appreciable energy savings are expected in power requirements for stock supply. Typically machine drives and vacuum pumps are electrically powered. To assess the relative magnitudes of the overall energy saving, the electrical energy saving can be weighted by a factor of 3 to allow for the relative generation efficiencies of bought electricity and on-site steam.

No direct energy saving is expected in the press section. However, the increased permeability of the high consistency sheet will produce a 2% increase in sheet consistency entering the dryer section for a wide range of machine speeds and basis weight sheets. A 10% reduction in steam usage will result. The increased sheet permeability is also expected to increase drying efficiency 10%. A total saving of approximately 20% is expected for the dryer section.

The sheet permeability is taken to be an important indicator of high consistency formation and is the basis for most of the energy savings. Both water and air permeabilities contribute. The wet permeability affects gravity, table roll, foil and wet suction drainage and press action. The air permeability is important in suction box and couch drainage and dryer action. Permeability tests carried out on high and low consistency sample sheets are described in section 7.5.

An assessment of the magnitudes of energy saving through high consistency forming is summarized in the following table.

	Section	Proportion of Total Machine Consumption %	Energy Saving Through HCF	
			% of Section	% of Total
Electrical Energy	Fourdrinier Drive	5	40	2
	Fourdrinier Vacuum	5	10	0.5
	Stock Pump	3		
Thermal Energy	Stock Preparation	5	40	2
	Dryer	70	20	14

The total saving in direct electrical and thermal energy is potentially 18.5%. No allowance has been made here for the weighting factor appropriate to electrical power generation. The limited amount of published data (References 2, 3) on the subject of high consistency forming tends to support this contention. An important aim for the present contract with the Department of Energy is to substantiate the existing results if they are valid.

As strength properties in the plane of the sheet are lower for paper formed at high consistency, suitable products will be those where these properties are not critical. Typical examples are pulp sheets, corrugating medium, and some multi-ply sheets such as folding boxboard where center-ply bulk is desired. The analysis in Section 5 suggests that the greatest improvements in sheet dryness due to pressing can be expected with high basis weight sheets of this type. Similar arguments suggest that the greatest increases in drying efficiency will also be observed with high basis weight sheets. Because of the large annual production rates associated with these grades, the total energy saving potential is high.

Figure 4.1 Comparison of Wet End Loops and Water Removal for High and Low Consistency Forming.

5. PRESS MODELING

One of the primary arguments for high consistency forming is that more water will be removed in the pressing process. A large body of literature on pressing exists. Most of the controlling factors have been identified, but as yet, a complete model capable of successfully predicting press performance has not been developed. A brief review of the more pertinent literature is presented below. These concepts are incorporated into a simplistic press model. Although not sufficient for predictive purposes, the model indicates the regimes in which a sheet formed at high consistency can be expected to produce energy savings.

5.1 Compression of Fibrous Sheets

One of the easiest aspects of pressing to study is static compression of wood fibers. Not very surprisingly, this subject has been studied in detail. A good review of this subject has been published by Han (Reference 4). In most of these experiments, the fiber concentration, ζ , is defined as the mass of fiber per unit volume (g/cm^3). Note that fiber concentration, ζ , is not the same as the sheet solids content, c , normally referred to by papermakers. Refer to the List of Symbols for complete definitions of symbols. These two measures of concentration have been developed because they are easy to measure. The moisture/fiber ratio, m , is defined as the ratio of the mass of moisture with respect to the mass of fiber in the sheet. The moisture ratio is more useful mathematically than the two concentration measures. The moisture/fiber ratio, m , is related to the fiber concentration, ζ , and the solids content, c , as follows:

$$m = \rho_w \left(\frac{1}{\zeta} - \frac{1}{\rho_f} \right) = \frac{1-c}{c} \quad \text{Equation (5.1)}$$

where $\rho_w = 1 \text{ g/cm}^3$ is the density of water and $\rho_f = 1.6 \text{ g/cm}^3$ is the density of the individual wood fibers.

In a typical static compression test, a sheet sample, saturated with water, is sandwiched between two flat plates. The sheet is subjected to a series of compressive loads, and allowed to reach equilibrium conditions (generally requiring 5-10 minutes) at each loading. From the clearance between the plates at each equilibrium condition, and the dry weight and sample size, the fiber concentration can be determined at each load. The data generally falls along a line described by equation (5.2) for a fairly wide range of compressive loads

$$\zeta_s = M P_s^n \quad \text{Equation (5.2)}$$

where M and n are empirical constants, dependent on the fiber characteristics, P_s (dynes/cm^2) is the compressive pressure, and ζ_s is the static fiber concentration. The subscript, s , signifies that the sheet has reached equilibrium conditions at the indicated pressure.

It is important to emphasize that the compressive response of a sample sheet is dependent on the previous compressive history. Typically a sheet sample is formed and transferred to the compression cell at fiber concentrations below one-tenth of a gram per cubic

centimeter ($z < 0.1$). The first compression of the sheet is the first time the sample is subjected to the series of increasing compressive loads. If the sample is rewetted and subjected to a second compression, the values of the power law coefficients, M and n , describing the compressive response will change. On the second compression, the sample generally reaches the same fiber density it had during the first compression at a lower compressive load. This is believed to be the result of plastic deformation and rearrangement of the individual fibers. This behavior is important when conducting experiments on samples which have already been subjected to a compressive cycle. In the subsequent discussion of the published data, all the correlations are based on first compression data.

As described in subsequent paragraphs, the sheet compression in a conventional press nip is by no means static, as the dwell time in the nip is generally less than fifty milli-seconds. It is quite difficult to study dynamic sheet compression in the field, but there are two references (References 5, 6) which describe apparatus for performing dynamic sheet compression tests in the laboratory. In both cases, the tests were conducted with a surface on one side of the test sheet which was impervious to the flow of water and on the other side, a porous surface. When the two surfaces are forced together, water flows through the sheet and out of the porous surface, thereby simulating the flow in a press nip with a single felt above the sheet (see figure 5.1a). A hydraulic pressure gradient develops in the sheet to produce the flow. At the interface between the sheet and the porous surface, (felt side), the hydraulic pressure is negligible. However, the hydraulic pressure at the impervious surface can be

equal to the compressive load at high rates of compression. The amount of actual fiber compression which takes place is governed by the difference between the applied compressive load and the hydraulic pressure at a given location in the sheet. Thus, the maximum local fiber compression occurs at the sheet felt interface (porous surface). At this location, the fibers carry the entire compressive load and the fiber concentration is equivalent to that which would be reached under a static compressive load. As the hydraulic pressure, necessary to produce flow through the sheet, increases towards the impervious surface, the local fiber concentration decreases. The local fiber concentration reaches a minimum at the impervious surface. Figure 5.2 is a representational drawing of how the hydraulic pressure and fiber concentration would vary across the sheet under these conditions. At any given instant in time, under these conditions, the mean fiber concentration for the sheet, $\bar{\zeta}$, is considerably lower than ζ_s , the fiber concentration which would be produced by the same load under static conditions. We define the difference between the fiber concentration produced by dynamic and static compression at the same load as $\Delta\zeta$. $\Delta\zeta$ is a function of the initial sheet moisture/fiber ratio, m , the sheet basis weight, b , and the time history of the compression cycles prior to the measurement.

For the series of experiments reported by Nai Chang (Reference 5), the initial moisture/fiber ratio, m , and the final (maximum) compressive load reached at the end of the cycle were

held constant. Each freshly made sheet sample was subjected to one, first compression, cycle. The duration of the compressive cycle and the bone dry basis weight of the samples were varied. The mean fiber concentration, ζ , was reported for each sample at the end of the first compression cycle. The time history of all the compressive cycles were similar, that is, the rate of pressure rise decreased with time, but the time, Δt , required to reach the final (maximum) compressive load varied. The compressive cycle is characterized by r_p , which is the final pressure divided by Δt .

The effects of dynamic compression presented by Chang have been analyzed in terms of the dimensionless ratio, $\Delta\zeta/\zeta$, observed at the end of the compression cycle. Here $\Delta\zeta$ is defined as a decrement in concentration, i.e. $\zeta = \zeta_s - \Delta\zeta$. Equation (5.3) provides a reasonable fit to the data in Chang's Table 4; a comparison between the observed data and this empirical fit is shown in Figure 5.3.

$$\Delta\zeta/\zeta_s = \frac{1}{50.83 - 2.27 \ln r_p} \quad \text{Equation (5.3)}$$

This is solely an empirical fit to the data presented and is not based on a physical model. The equation shows the appropriate trend, that is, the difference between the mean fiber concentration under dynamic compression and the fiber concentration which would be reached under static compression increases as r_p increases; but it also suggests that when r_p equals 3.4×10^9 dynes/cm².sec there will be no compression at all which is obviously not a physical reality. Equation (5.3) is not valid for $r_p > 3.4 \times 10^9$ dynes/cm².sec. The basis weight for each of the trial sheets during this series of runs was almost the same, with a mean value of 0.0388 g/cm².

Chang's Table 5 presents the effect of basis weight on $\Delta\zeta/\zeta_s$ at fixed r_p . The average rate of pressure rise during this series of experiments was $r_p = 1.02 \times 10^9$ dynes/cm².sec. To combine the results of Chang's two series of experiments, a multiplicative correction factor was developed for equation (5.3). The values of $\Delta\zeta/\zeta_s$ and b derived from Chang's Table 5 were normalized with respect to the basis weight (0.0388 g/cm²) used in the first experiments, and the ratio of $\Delta\zeta/\zeta_s$ (0.267) predicted by equation (5.3) for $r_p = 1.02 \times 10^9$ dynes/cm².sec. Figure 5.4 indicates that the normalized basis weight, $b/0.03888$, is linearly proportional to the normalized change in fiber concentration, $\Delta\zeta/0.267\zeta_s$.

This empirical fit can be related to a simple physical model. One would expect that as the basis weight approached zero, the flow of water through the sheet would also approach zero therefore, the hydraulic pressure gradient must approach zero. Under these limiting conditions, there would be no difference between static and dynamic compression. Conversely, as the basis weight increases, the amount of water flowing through the sheet increases and consequently the hydraulic pressure gradient must increase. It follows that the change in fiber concentration due to dynamic compression would increase with basis weight.

These two correlations from Chang's data (equation(5.3) and figure 5.4), are combined to form equation (5.4). This equation shows the change in fiber concentration due to dynamic compression with respect to the fiber concentration which would be reached under static loading as a function of basis weight, b , and the rate of pressure rise, r_p .

$$\Delta \zeta / \zeta_s = \frac{b}{1.93 - 0.0863 \ln r_p} \quad \text{Equation (5.4)}$$

Although this equation is an empirical fit to a limited set of data, it shows the important functional relationship between basis weight and the rate of pressure rise. For a given peak pressure, P_s , the fiber concentration decreases with increase of either basis weight or rate of pressure rise.

A final piece of data obtained from Chang's study for this report is that the fiber concentration as a function of static pressure can be approximated by equation (5.5).

$$\zeta_s = 0.0085 P_s^{.266} \quad \text{Equation (5.5)}$$

Note that the final pressure used in Chang's experiments was 4.8×10^7 dynes/cm². Thus in the above, $\zeta_s = .941$, which is much higher than the fiber concentration observed after a typical press section. This taken in conjunction with the empirical nature of equation (5.5) and the fact that all results were for first compression experiments suggest that equation (5.5) should only be used as a general guide to the behavior expected in a press nip.

5.2 Press Nip Operation

Felt compression has, to date, not been given the attention that it is due, even though it is relatively easy to measure. However, there are some published papers which deal with this subject (References 7-10). The uncompressed felt thickness ranges between 0.2 and 0.45 cm. At typical press loadings, the felt compresses to a thickness on the order of half the initial thickness. Using these crude estimates, it is assumed that the felt undergoes a change in thickness varying between 0.1 and 0.25 cm between the beginning of the press nip and the middle of the press nip. Note that in a typical press nip this is much greater than the change in thickness of the sheet. Therefore, to first order, the compression of the felt governs the pressure distribution in the press nip and the compression of the sheet can be ignored, while calculating the press nip pressure distribution.

There are several good summaries of the dynamics of a press nip (References 11-13). Early presses had two plain rolls, which were impervious to the flow of water, through which a sheet and felt were passed. During compression, water flowed out of the sheet, in a direction perpendicular to the plane of the sheet, into the felt. This water was either carried out of the press nip in the felt or flowed laterally through the felt in the direction opposite to the felt motion and emerged on the upstream side of the press nip. This type of press nip is referred to as either a lateral flow press or a plain press. More recently, presses have been developed with one press roll having an impervious surface and the other having void spaces, which may have

suction applied to them, allowing fluids to flow out of the felt into the void spaces. In this type of press the flow of water is perpendicular to the plane of both the sheet and the felt. This type of press is generally called a transverse flow press. The two most common types of transverse flow presses have either grooves in the press roll surface or drilled holes with suction beneath them. For present purposes, it is assumed the press is designed such that the flow resistance of the felt, either lateral or transverse, is very small compared to the flow resistances within the sheet. With this assumption, it makes no difference whether the press design is lateral or transverse.

From the beginning of the press nip to the press nip center line, as the sheet is compressed, the sheet felt dynamics are fairly well understood. However, after mid-nip, the sheet felt combination goes through a decompression phase which is not as well understood. It is generally accepted that because the capillary structure of the sheet is smaller than that of the felt, the sheet pulls some of the water back out of the felt which was pushed into it during the compression phase. However, the mechanics of this phenomenon are not very well understood and no adequate models exist. The analysis has been limited to the compression phase in the press nip.

In a typical paper mill situation, the machine speed, sheet basis weight, type of felt, press nip geometry, and lineal loading in the press nip, P' , (dynes/cm), will be known. The actual press nip pressure distribution must be derived. Figure 5.1b indicates a simplified press nip configuration where the top and bottom roll are rigid, uncovered, and of equal diameter (see Scheil, Reference 9 for details of press nips with rubber-covered rolls). The change in thickness of the

sheet felt combination between the entrance to the nip roll, point 1, and mid-nip, point 2, is defined as Δz . As explained above, Δz is very nearly equal to the change in the felt thickness. The geometry of this situation can be used to define the nip half-length, Δx , between the beginning of the nip and mid-nip in equation (5.6).

$$\Delta x = \sqrt{\frac{\Delta z D}{2} - \frac{(\Delta z)^2}{4}} \cong \sqrt{\frac{\Delta z D}{2}} \quad \text{Equation (5.6)}$$

where D is the roll diameter. Since D is much greater than Δz , the approximate form can be used where the second order term, $(\Delta z)^2$ is dropped.

Although it is not critical in a simplistic analysis of this nature, observed pressure distributions in the press nip are generally sinusoidal (References 9, 10, 13-15). Since compression of the sheet is ignored in comparison to the compression of the felt, the total pressure distribution is symmetrical about mid-nip and takes place over a width of $2\Delta x$. If a sinusoidal pressure pulse is assumed, the point-to-point pressure $P(x)$, (dynes/cm²), can be inferred from the lineal press loading, P' . The integral of the local pressure, with respect to distance through the nip, must be equal to the lineal press load. The maximum pressure at mid-nip, $P_{\max}$, is then given by equation (5.7).

$$P_{\max} = P' \frac{\pi}{4\Delta x} \cong P' \frac{1.11}{\sqrt{\Delta z D}} \quad \text{Equation (5.7)}$$

This simple model of the pressure distribution in a press nip can be combined with Chang's experimental work on dynamic fiber

compression to calculate fiber concentration at mid-nip. Fortuitously, the pressure rise with time in Chang's apparatus is similar to the sinusoidal pressure profiles observed in typical press nips. It follows that the maximum pressure, $P_{\max}$, divided by the time required for the sheet to travel from Point 1 to Point 2 (mid-nip), $\Delta x/U$, can be used for the value of r_p to characterize the compressive cycle in the press nip:

$$r_p = \frac{P_{\max} U}{\Delta x} \approx \pi P^1 U / 2 \Delta z D \quad \text{Equation (5.8)}$$

where U is the machine speed.

The solution for r_p can be used with equation (5.4), to determine the effect of changes in press geometry and operating conditions. To increase final fiber concentration after the press section for a sheet with a given basis weight, b , the rate of pressure rise in the nip, r_p , must be decreased without decreasing $P_{\max}$. Low machine speeds, U , should produce high final fiber concentrations, which in turn will result in an energy savings for each pound of paper produced. However, the economics of the paper industry do not favor low speed operation.

A more viable solution for the paper industry is to increase the nip width while maintaining a fixed peak pressure, $P_{\max}$. This implies that the lineal load must increase at the same rate as the nip width. Deformable roll covers and press rolls are currently being used to increase press nip widths. The new press configurations are operated at correspondingly higher lineal loads.

As indicated in equation (5.3), high basis weight sheets are particularly sensitive to rapid compression rates. Running the sheet

through the press nip sandwiched between two felts doubles both the surface area through which water can flow out of the sheet and the total felt compression. In this configuration (double felted), the hydraulic pressure is minimal on both sides of the sheet and reaches a maximum at the sheet center line. The flow, during the compression phase, in the top and bottom halves of the sheet is, by symmetry, the same as the process described in the preceeding paragraphs for a press nip with a single felt. It follows that double felting produces an effect at mid-nip equivalent to cutting the basis weight in half and increasing the nip length by $\sqrt{2}$. At high rates of compression, this has a strong effect on the fiber content at mid-nip. The disadvantage is that the amount of water pulled back into the sheet from the felt during the decompression phase doubles along with the surface area in contact with the sheet. A better understanding of this "rewetting" phenomenon is required to define the break-even point for double felting.

5.3 Implications for High Consistency Forming

The major reason for the energy savings anticipated with high consistency forming is that the sheet should have lower resistance to fluid flow perpendicular to the plane of the sheet. This reduced flow resistance is a result of the "felted" fiber orientation in a high consistency sheet (refer to sections 5.1 and 7.5 for details). For a given press configuration and set of operating conditions, a reduction in sheet flow resistance will result in lower hydraulic pressures throughout the sheet. If the hydraulic pressures are lower, a larger fraction of the compressive load is transmitted to the fibers and a higher mean fiber concentration will result.

The reduction in flow resistance in a high consistency sheet must be relatively small, or the change in sheet solids content, c , of a high consistency sheet leaving the press would be greater than the 2% value reported by the Scandinavians (References 2, 3). It follows that before a measurable difference between the final solids content of sheets formed at high and low consistency can be observed, the pressing process must be strongly affected by the hydraulic pressure gradient created by dynamic compression. Conversely, one would not expect to see a significant difference during static compression.

Arbitrarily it is assumed that $\Delta\zeta/\zeta_s$ must be greater than 0.3 before the lower flow resistance of the high consistency sheet can be expected to have a significant effect on sheet pressibility. Using this value, equation (5.4) can be solved for the minimum rate of pressure rise required to produce a significant effect with the type of fibers used in Nai Chang's experiments (See Section 5.1):

$$r_p > \exp (22.36 - 38.6 b)$$

Equation (5.9)

Conversely, the minimum basis weight as a function of pressure rise becomes:

$$b > 0.579 - .0259 \ln r_p$$

Equation (5.10)

Note that these equations are not valid for $r_p > 3.4 \times 10^9$ dynes/cm² ·sec.

As an example, assume a fairly typical press nip configuration.

Table

Press Roll Diameter, D	90 cm	(3 feet)
Lineal loading, P'	3.5×10^7 dynes/cm	(200 pli)
Felt compression in nip, Δz	0.15 cm	(.06 inches)

Equation (5.8) can be used with this data to find the rate of pressure rise, r_p , as a function of machine speed, U.

$$r_p = 4.1 \times 10^6 \times U$$

Equation (5.11)

By combining equations (5.9) and (5.11), the minimum machine speed can be calculated for which increased water removal is expected in the press section with a sheet formed at high consistency. The table below indicates this minimum machine speed for three typical grades of paper.

Paper Grade	Typical Basis Weight b (g/cm ²)	Minimum Speed for Increased Water Removal	
		U (cm/sec)	(ft./min.)
Pulp Sheets	.064	106	509
Linerboard	.020	580	1143
Newsprint	.005	1000	1970

Note that other press configurations, types of wood fiber, and the effects of the multiple compressive cycles the sheet experiences in a typical press section will in practice cause significant variation from the minimum speeds listed in the preceding table.

Although the numerical values in the preceding analysis may not be correct, the general trends are. Energy savings are not expected from pressing high consistency sheets unless both the machine speed and basis weight are relatively high. This dovetails nicely with the feeling that it is easier to develop a high consistency headbox, with appropriate flock breaking capability, for high speed and high basis weight applications.

Figure 5. 1a Elements of a Dynamic Compression Cell

Mechanism for monitoring and applying compressive load capable of creating rapid changes in applied load

Figure 5. 1b Typical Nip Configuration

Figure 5.2 Pressure Distribution in a Sheet Sample during Dynamic Compression

Fiber Concentration Distribution in a Sheet Sample during Dynamic Compression

Figure 5.3 Effect of Pressure Rise
at Constant Basis Weight

Figure 5.4 Effect of Basis Weight
at Constant Pressure Rise

$$r_p = 1.02 \times 10^9 \text{ (Dynes/cm}^2\text{sec)}$$

6. ANALYTICAL MODEL OF THE PAPER DRYING PROCESS

In analyzing and calculating the performance of a dryer section, it is assumed that the average drying rate for the dryer section is mainly a function of the temperature of the steam supply. The drying rate is defined as the mass of water evaporated from a unit area of the sheet in unit time (Reference 16). For a given machine configuration and paper grade the average rate is independent of machine speed. The specific steam consumption, defined by mass of steam to evaporate a unit mass of water from the sheet, also has a constant value, typically in the range 1.5 to 2 kg of steam per kg of moisture evaporated. With these simple assumptions, it is easy to establish the sensitivity of the dryer performance to changes in sheet consistency out of the press section. Consistency is here defined as the ratio of the fiber mass to the mass of fiber and water in the sheet. For example, a sheet with 1% higher consistency c_0 at dryer section entry will result in either a 3 to 5% increase in production or a 3 to 5% decrease in steam consumption. It is this result which emphasises the importance of removing as much water as possible ahead of the dryer section. However, there are some serious limitations with this over-simplified model, particularly in estimating sheet dryness at the reel accurately. The model does not give any feel for the physical length of the dryer section or any measure of the distribution of sheet consistency down the machine in the dryer section.

At the other extreme of modeling, a step-by-step heat and mass transfer process can be developed, incorporating the effects

of single or double felting, pocket ventilation, etc. Such a sophisticated model is not required for the present purpose of assessment of the energy saving impact of new technology such as high consistency forming. A compromise has been reached by extending the simple model to take account of the variation of local drying rate with local sheet consistency. It has been established (Reference 17) that for a wide range of paper products, drying is characterized by three regions. In the first (small) region, the sheet is heated up to some equilibrium temperature. In the second, the drying rate per unit area of sheet is constant up to a critical sheet consistency c_c . Beyond this point and in the third region, the drying rate falls with increasing dryness. In the present model, the first region is neglected and the other two are expressed mathematically by:

constant drying rate region: $c_o < c < c_c$

$$r(t) = -b \frac{dm(t)}{dt} = R, \text{ constant} \quad \text{Equation (6.1)}$$

falling drying rate region: $c_c < c < c_e$

$$r(t) = -b \frac{dm(t)}{dt} = R \frac{m(t)}{m_c} \quad \text{Equation (6.2)}$$

where c = sheet solids content or consistency, defined by
mass of fiber/(mass of fiber and water).

m = moisture/fiber ratio. Note that $m = (1-c)/c$.

$r(t)$ = drying rate for the sheet in mass of water per
unit area per unit time.

b = sheet bone dry basis weight.

R = value of drying rate in the constant rate region

and the subscripts denote the following conditions:

- o - at entry to the dryer section
- c - at the critical state between constant and falling rate regions.
- e - at the dryer section exit or reel.

The relationships in equations (6.1) and (6.2) are shown graphically in Figure 6.1. The form for equation (6.2) was obtained by empirical fit to the data published in Reference 17, which was also used as a source for representative values of m_c and c_c . The value of R is a function of steam pressure, felt configuration, dryer cylinder condition, ventilation arrangement and type of sheet, but largely independent of machine speed. Empirical values for R can be obtained for typical installations using the published mean evaporation rates (Reference 16).

Equations (6.1) and (6.2) are differential equations in the variable m which can be easily integrated to obtain the variation of sheet moisture/fiber ratio as a function of time and hence as a function of distance down the machine at a given machine speed. Upon integration and applying the appropriate initial conditions, the results can be expressed in terms of sheet consistency c for the two regions as:

$$c_o < c < c_c$$

$$\tau = 1 - \frac{c_o}{c} \quad \text{Equation (6.3)}$$

$$c_c < c < c_e$$

$$\tau = \frac{1}{c_o} - \frac{1}{c_c} + \frac{(1-c_c)}{c_c} \ln \left[\frac{(1-c_c)}{c_c} \frac{c}{(1-c)} \right] \quad \text{Equation (6.4)}$$

where τ is a non-dimensional time defined by:

$$\tau = \frac{tR}{b} \quad \text{Equation (6.5)}$$

This can be related to location in the dryer section by:

$$\tau = \frac{Rx}{bU} \quad \text{Equation (6.6)}$$

where x = distance along the sheet run from dryer entry

and U = the machine speed

The excellent agreement between measured data (Reference 17) and the theoretical model represented by equations (6.3), (6.4), and (6.5) is illustrated in Figure 6.2. Substitution of the desired reel consistency ($c = c_e$) in equation (6.4) gives the required dwell time τ_e , and hence length, for the dryer section. For the majority of machines τ_e lies in the range 2 to 3. Using this value it is then possible to determine the sensitivity of the dryer to incremental changes in the dependent variables such as speed, basis weight, production and the various sheet consistencies. It can further be assumed that the steam consumption S is proportional to the evaporation rate R . Substituting τ_e from equation (6.6) and c_e in equation (6.4) and using logarithmic differentiation on the result yields the following:

$$\frac{\Delta S}{S} - \frac{\Delta b}{b} - \frac{\Delta U}{U} = \frac{1}{\tau_e} \frac{(1-c_e)}{c_c c_e (1-c_e)} \Delta c_e - \frac{1}{\tau_e} \frac{1}{c_o^2} \Delta c_o \quad \text{Equation (6.7)}$$

where ΔS , Δb , ΔU , Δc_e and Δc_o are the incremental changes in steam consumption, basis weight, machine speed, reel consistency c_e and entry

consistency c_o respectively.

To illustrate the use of equation (6.7), typical values for a paper machine are chosen. The critical consistency, c_c , lies in the range 70-80% and is taken as 75% here. Other values assumed are $c_o = 35\%$ and $c_e = 95\%$, and τ_e can then be obtained from equation (6.4) as 2.14.

EXAMPLE 1

Basis weight, machine speed and reel consistency are unchanged. Equation (6.7) then gives $\Delta S/S = - 3.81 \Delta c_o$, which means that a 1% drier sheet into the dryer section results in a 3.8% reduction in steam consumption. In a similar way, there could be a 3.8% increase in machine speed for the same steam consumption.

EXAMPLE 2

Figure 6.3 shows the sensitivity of steam consumption to change in dryer section entry dryness over a wide range of sheet consistencies at entry. This shows that with current day press configurations which produce values for c_o in the range 0.35 to 0.4, there is a large return in steam and energy saving by increasing the sheet dryness. However, as the sheet dryness reaches values of 0.55, there is much less return by way of steam reduction with further increase of dryness. In view of the mechanical complexities of high press load and long nip duration required to produce sheet consistencies of 55%, it can be concluded that there is a point of diminishing return for trying to increase sheet dryness out of the press section. This point has not yet been reached with present day press configurations.

EXAMPLE 3

The sensitivity of the reel dryness c_e to machine speed U and dryer entry consistency c_o can be obtained from Equation (6.7) by setting ΔS and Δb to zero to give:

$$\frac{\Delta U}{U} = - 3.28 \Delta c_e + 3.81 \Delta c_o$$

This shows that a 3.3% change in machine speed is needed to change reel moisture by 1%. For a constant machine speed, a 1.2% change in entry dryness will produce a 1% change in reel moisture. The reel moisture is, therefore, three times as sensitive to entry dryness as it is to machine speed.

In this section, a simple, realistic and useful dryer section model has been developed in order to provide a means for assessing the energy savings potential. Examples of its application have been presented and the results obtained give support to the claim that if high consistency forming produces a sheet with 1 to 2% higher consistency out of the press section, then there will be a 5 to 10% steam consumption saving in the dryer section.

Figure 6.1. Model of Drying Rate

Figure 6.2. Comparison of Measured Data and Theoretical Model for Sheet Dryness

Figure 6.3. Effect of Sheet Dryness on Steam Consumption

7. EXPERIMENTAL WORK

This section contains a description of all the experimental work carried out under Phase I of the contract. The topics range from initial handsheet studies through fabrication of the dynamic former to development of a new headbox for low speed operation and the preliminary testing of the formed sheets. This progression reflects the development of the work as described in Section 2.

7.1 Properties of High and Low Consistency Handsheets

Two techniques for forming a mat with the felted fiber structure associated with high consistency sheets were attempted using traditional handsheet techniques. Preliminary static compression and yield strength tests were conducted on these sheet samples. The results of these trials and the conclusion that a dynamic forming technique is required to produce representative high consistency sheets is presented in section 7.1.1. This conclusion led to the change in program emphasis to include construction of a dynamic former as discussed in Section 2. The analysis of sheet properties during the remainder of the Phase I contract period was devoted to the compressive response of low consistency handsheets, described in section 7.1.2, and the permeability of both high and low consistency sheets which is covered in Section 7.5.

7.1.1 Initial Examination of Handsheets

A handsheet is a sheet sample which is formed by draining an initial quantity of stock through a stationary wire. The process is "static" in the sense that the stock is mixed in a container above the wire and then allowed to drain, without agitation, through the wire

depositing a sheet on the top side of the wire. The only motion or action is the vertical drainage of the stock. The term "dynamic forming", as used in this report, refers to a process where there is agitation of the stock during or within milli seconds of the drainage process which forms the sheet.

Typically dynamically formed low consistency sheets have a layered structure where the fibers are all oriented in the plane of the sheet (x and y axis), while high consistency sheets have a felted structure where some of the fibers are cross-linked in the z direction, perpendicular to the plane of the sheet. Because of the z direction cross-linking the high consistency sheet is expected to have higher z direction strength and permeability than a sheet formed at low consistency. It has been reported (Reference 2) that the z direction strength of a high consistency sheet can be twice that of a conventional sheet, while differences resulting from pressing are on the order of several percent. It was concluded that the simplest and most reliable test for the felted structure associated with high consistency sheets was a z direction strength test.

In the following discussion, conventional handsheet refers to a sheet formed in a handsheet former at consistencies below 0.05% solids content. This is low enough that the fibers do not interact with each other until they reach the wire, providing the drainage rate is high enough to prevent sedimentation. With this "conventional" filtration technique, the individual fibers lie down in the plane of the sheet when they reach the fibers already deposited on the wire, producing a layered sheet, with the fibers oriented in the x and y plane.

In April, 1978, an attempt was made to form a felted high consistency type structure from relatively low consistency bleached stock using a thickening rather than a filtration technique. For this stock, the sedimentation consistency was on the order of 0.2%. If a stock sample is well agitated at a consistency below the sedimentation consistency, it will settle out in a random fiber network at 0.2%. By draining such a network very slowly, in the handsheet former, it was hoped the random orientation of the fibers would not be disturbed, and a felted sheet structure would be produced.

Handsheets were formed in the conventional manner and from sedimentary stock as described above. Both types of handsheet were hand pressed with a roller and air dried. The z-direction strength of the samples was tested, but there was no significant difference between the yield strengths of the two sheet sample types. It is hypothesized that a felted structure was not produced because the large distances between individual fibers in the low consistency sedimentary stock prevents the formation of a sufficient number of z-direction cross-linkages. The number of linkages stays the same as the sheet is thickened by the slow drainage process and the final sheet has no more z-direction cross-linkages than existing in the initial mixture of stock. If this simple model is correct, the number of z-direction cross-linkages and the resulting z-direction strength and permeability should increase as consistency of the initial stock mixture increases.

Following this argument, handsheets were formed from high consistency stock. However, it is very difficult to form an acceptable high consistency handsheet because of the stock's tendency to form flocs in the handsheet former, and the relatively low volumes of stock

that are involved. For example, the basis weight of the TAPPI standard handsheet is 60 g/m^2 . At 3% consistency, the depth of the layer of stock required for this basis weight is 0.2 centimeters while a conventional handsheet formed at 0.05% consistency requires a stock depth of 12 centimeters which is much easier to agitate and control prior to sheet formation. Even with heavier sheets in the linerboard basis weight range, the high consistency stock depth in the handsheet former is much too shallow to allow agitation of the stock in the former. The high consistency handsheets produced are highly flocculated due to the lack of proper agitation immediately prior to the drainage phase.

In May, 1978, three sets of handsheets were formed in the 200 g/m^2 basis weight range. Each set consisted of three sheets formed from 0.5% consistency stock and three sheets formed from 3.0% consistency stock.

Preliminary static pressing experiments were performed on these sheets. All six sheets from a given set of handsheets were placed between pieces of filter paper and simultaneously pressed between flat plates while the loading pressure was held at 60 psi. Final sheet consistencies after equilibrium was reached were in the range of 40% solids which is in the same range as the sheet consistency after the press section on a conventional paper machine.

On the first two sets of handsheets, there was no significant difference between the final consistency of the sheets formed at high, 3.0%, and low, 0.5%, consistency. The third set of handsheets was pressed with a plastic sheet between the sheets formed at high and low consistency to prevent flow between the two sample groups. The final consistency of the low consistency handsheets was slightly lower than that of the high consistency handsheets. As these results

did not agree with the limited pressing data on high consistency sheets (Reference 2), it was taken as an indication that the appropriate felted structure was not achieved in the high consistency handsheets. However, it was recognized that this type of pressing experiment is not conclusive because:

- 1) The high degree of flocculation in the high consistency handsheets could adversely affect pressing.
- 2) Static compression tests of this type are not representative of the dynamic processes occurring in the press nip of a paper machine.

In June, 1978, a series of z-direction yield strength tests were conducted on handsheet samples formed at high and low consistencies. The guidelines from TAPPI Standard Testing Procedure #T-506 (Reference 18) were followed.

The Tappi testing procedure recommends conditioning the samples in a constant temperature and humidity environment before testing. Although a conditioning room was not available when comparison strength tests were performed, all the samples from a given group were stored in the same environment. Thus the sample conditioning was the same for each group of samples tested. However, the conditioning varies between groups. Each sample in a given group was subjected to the same press loading during preparation, but the same press load was not applied to all groups. These two factors cause a wide range of yield strengths between groups. As shown in the table below, the variation between yield stress for the high and low consistency handsheets is not statistically significant for any of the groups tested.

MEAN YIELD STRESS (psi)

	Handsheets formed with 0.5% Bleach Stock	Handsheets formed with 3% Bleach Stock
Group A	18.5 $\pm$ 2.2	15.3 $\pm$ 6.4
Group B	10.3 $\pm$ 2.2	12.1 $\pm$ 1.3
Group C	27.6 $\pm$ 2.3	25.6 $\pm$ 2.5

Primarily because there was no significant difference in the high and low consistency handsheet z-direction strength, it was concluded that the appropriate felted structure of a high consistency sheet could not be achieved using handsheet techniques. This conclusion indicated that it would be necessary to impliment one of the dynamic forming techniques, outlined in Section 7.2, to produce the felted structure and minimize flocculation in the sheet samples.

7.1.2 Low Consistency Handsheet Compression Response

During the balance of the contract period experimental techniques for measuring permeability and the compression response of sheet samples were developed while the dynamic former was constructed. Two techniques have been used to determine the relationship between the compressive pressure and the fiber concentration during static compression. Both techniques sandwich the sample between two flat stainless steel plates. The force applied to the top plate is held constant as the water seeps out of the void spaces allowing the sheet sample to compress. Equilibrium is reached when the sheet compression stops. Once the sample is in equilibrium, the compressive load is carried by the sheet fibers. It generally takes ten to fifteen minutes at each applied force to reach equilibrium conditions. The static compressive pressure P_s is calculated by dividing the applied force by the area of the sample under compression. A series of measurements is taken to determine

the fiber concentration, ζ , at progressively higher pressures for each sample.

The first determinations of the fiber concentration, ζ , were made by measuring the moisture content for each loading of the sample sheet after equilibrium was reached. The samples were removed from the press plates and weighed after each equilibrium. To minimize water loss by evaporation during the weighing process, the samples were sandwiched between plastic sheets. After the compression run was completed, the sample was dried in the oven and the dry weight was determined. The moisture/fiber ratio, m , was determined from the ratio of the wet to dry sample wet. The fiber concentration, ζ , was then determined with Equation 5.1 assuming $\rho_f = 1.6 \text{ g/cm}^3$. The results obtained with this technique are in agreement with data for other wood pulps (Reference 4) and can be approximated by the power law relationship of Equation 5.2. However, the procedure is quite time consuming with the repetitive weighing and calculations. A potential source of error is also introduced by removing the sample from between the press plates for each weighing and then attempting to replace the sample in the same location.

As the permeability experiments continued, it became apparent that a better method of controlling the fiber concentration was required. To accomplish this, a second method, the one generally referred to in the literature, of determining fiber concentration was employed. A special set of press plates was fabricated so that the separation

between them, which corresponds to the thickness of the sheet, could be measured after each equilibrium condition was reached. After a series of measurements of thickness versus load, the sample is removed and the dry basis weight, b , is determined. The fiber concentration is calculated from the basis weight and sheet thickness, and the data can be plotted as in figure 7.2.

Both methods give equivalent results, although the second method is easier and gives greater accuracy. Preliminary studies have been conducted on handsheets formed at low consistency. The results have been reduced to cgs units and are presented in figure 7.2. The first compression data for both the bleached and unbleached pulps which have been tested can be characterized by the solid line in figure 7.2. However, when the bleach pulp was rewetted and subjected to second compression, a significantly different response, indicated by the dashed line, was observed.

The maximum compressive pressure during the first compression run of February 19, 1978, was $P_g = 3 \times 10^6$ dynes/cm². When this pressure was reached on the second compression with the same sample, the fiber concentration from the second compression was equal to that observed during the first compression. At all lower compressive pressures the second compression fiber concentration was higher than the first compression fiber concentration. Although further study is required, the second compression response, at compressive pressures above the maximum pressure exerted during the first compression (3×10^6 dynes/cm² in this example), is expected to follow the first compression curve. This response is anticipated because it is the first time the fibers have been subjected to these higher pressures and, therefore, they are effectively

undergoing compression for the first time in this higher pressure range.

This type of behavior will be important when dynamic pressing studies are conducted on sample high and low consistency sheets. The high consistency sheets will be dynamically formed and, therefore, subjected to a different set of compressive loads during the forming process than the low consistency sheets formed in the handsheet former. To perform a meaningful dynamic pressing comparison, the high and low consistency sheets must both be pressed at higher compressive pressures than either sheet experienced during the forming processes. This should negate any residual effects from the compression cycles experienced during formation on the dynamic response of the sheet samples during the pressing experiment.

7.2 Conceptual High Consistency Dynamic Forming Designs

As detailed in Section 7.1, the initial **handsheet** experimentation indicated that a dynamic formation technique **was required** to form appropriate high consistency sheets. A **brief** review of the concepts envisioned and their relative merits **is given** in this section. Figure 7.3 depicts the various **conceptual designs**. The conclusion was that the **low speed headbox and fourdrinier** type forming region shown in figures 7.3g and 7.4 were the most practical.

The difficulty with handsheet techniques for high consistency stock are:

- 1) the volume is too low to permit effective agitation, and,
- 2) The effective viscosity is so high that any initial agitation damps out before the sheet can be formed.

Figures 7.3a and 7.3b depict two variations on the same theme. The design concept was to agitate a large tank of high consistency stock, and remove a small portion of the total volume under agitation with a special former. Figure 7.3a depicts an inverted handsheet former while figures 7.3b depicts a conventional cylinder former. Both ideas were rejected as no mechanism for controlling the eddy size or eliminating stagnation regions in the tank could be envisioned.

To produce the small scale eddies which are necessary to break up flocs, small scale dimensions are required. The most effective method of producing the required energy dissipation and eddy size is with the type of headbox design which can be used on a conventional fourdrinier table. Several configurations for forming a sheet sample with a headbox were considered.

Figures 7.3c and 7.3d represent concepts where a headbox geometry would be run with a continuous stock flow. When conditions were optimum, an air cylinder would be triggered to trap an individual segment of the discharge which would be dewatered subsequently. The difficulty with this concept is that when the sample was trapped, it would undergo rapid deceleration. It is reasonable to assume that this deceleration would be too abrupt to allow the sheet to retain the fine scale structure it had on exiting the headbox.

Figures 7.3 e, f and g represent designs where a wire or porous media is moved with respect to the headbox, allowing a sheet to be laid on a surface moving at the exit jet velocity. Configurations along the lines of 7.3b were considered where either the headbox moved over a fixed distance with respect to the wire or visa versa. The acceleration and deceleration regions required to produce an adequate match of the jet and wire speeds presented the major problem area. The rotating cylindrical forming region with a headbox traversing along the axis of the cylinder, depicted in figure 7.3f, allows significantly more time for acceleration and deceleration given the same space and operating speed requirements. However, in addition to a traverse mechanism, a rotating cylindrical forming section with internal vacuum would be required. The added complexity seemed prohibitive.

After reviewing these concepts, a headbox discharging onto a short fourdrinier table as indicated in figure 7.3g, appeared to be the most practical design. Once this was established, the questions of

size and speed were the major concern. The major difficulty with high speed operation is that the stock handling and storage requirements increase linearly with machine speed if run time is held constant.

A minimum run time of ten minutes was chosen to allow sufficient time to stabilize operating conditions and collect sheet samples. The Scandinavians (Reference 2) report difficulties forming high consistency sheets at speeds below 400 fpm, hence this was chosen as the minimum operating speed. As some of Lodding's high speed headbox design work was conducted with eight inch wide slice lips, eight inches was chosen as a slice width design point. The intended stock consistency range was 2½% to 3% solid content. Both headbox design considerations (Section 7.4) and pressing theory (Section 5) suggested that relatively high basis weight sheets would be easiest to form and to use in demonstrations of energy savings in the press section. A design point of 0.02 g/cm² or 40#/1000 ft² was chosen. This is a typical basis weight range for linerboard.

For the operating range outlined above, a 50 gpm stock delivery to the wire is required. A ten minute run requires a 500 gallon storage capability. Cost and space limitations dictated that the storage capability could not be significantly larger than this. Design work and a search for the required component parts such as the drive, pulper, vacuum pump, and storage tanks were initiated. The final design of Lodding's dynamic former is specified in section 7.3.

7.3 Lodding Dynamic Former

The Lodding Dynamic Former was completed and put into operation April 12, 1979. During April and May, a series of high consistency runs, detailed in section 7.4.4, were conducted. A general description of the dynamic former flow loops, instrumentation, and typical operating conditions is given below.

Figure 7.4 is a schematic representation of the dynamic former table. The table consists of a 22" wide Synweave design 272 wire (donated by Wisconsin Wires, Inc.) supported by 30" diameter rubber covered rolls at each end of the table. The roll centerlines are 12' apart which leaves an effective sheet forming length of 10'. The wire is driven by a 7.5 horsepower variable speed motor. The motor is equipped with a feedback control system which keeps the wire speed constant independent of load. Wire speed can be varied between 100 and 500 feet per minute. Beneath the forming section on the return run of the wire, there is a tensioning roll and an automatic guide roll which keeps the wire from running off the edges of the turning rolls.

Beneath the wire in the forming section there are eight suction boxes in which the vacuum levels can be controlled independently. The last four units in the forming section are designed for high vacuum levels and will be referred to as "flatboxes". Each flatbox has a polyethelene cover with a 10" machine direction length and an array of 1/2" diameter holes which leaves 20% of the surface area of the cover open to the vacuum in the flatbox. A vacuum pump creates the air flow through these holes into the flatboxes and the water which comes out of

the sheet, as a result of the air flow, is collected in a seal pit. This seal pit acts as a collection point for all the water which is removed from the sheet. The water is pumped from the seal pit up to either one or both of the two 1000 gallon holding tanks. The pump keeps the free surface of the seal pit 13' below the wire, therefore, the flatboxes cannot be run at vacuum levels above 11" of mercury without flooding.

Three low vacuum suction boxes, referred to as "Drainage Control" units are located in the middle of the forming region. These are designed for vacuum levels between zero and 3" of mercury. Each unit has three polyethelene foils mounted transverse to the wire on 4-3/8" centers above a single vacuum compartment. The foils support the wire and induce a small vacuum pulse below the sheet even if no suction is applied to the vacuum chamber.

A specially designed "slice suction" box is mounted under the headbox slice (see section 7.4.4) at the beginning of the formation region. This unit has five foils mounted on 4-3/8" centers with four individually controlled vacuum chambers, one for each of the gaps between the five foils. The headbox slice is above the first two vacuum chambers. The top of the sheet is open to the atmosphere above the last two chambers.

The vacuum levels in all eleven vacuum chambers are equipped with gauges or manometers. During a run, the vacuum readings for each compartment are recorded in the log book. Samples of the sheet produced by the headbox can be blown off the wire to check the sheet consistency at any location on the forming area after the headbox slice

lip. Blow samples are currently being collected in three locations: immediately after the slice lip, after the last compartment in the slice suction box, and after the last flatbox. Stock samples are also taken at the fan pump. The samples are immediately sealed in a plastic bag or bottle to avoid moisture loss, and weighed at the end of the run. The samples are dried overnight, and weighed again the next day, causing a twenty-four hour lag between sample collection and knowledge of the sample consistency.

A used 1000 gallon capacity pulper was obtained to slush the purchased pulp sheets, which were the source of the wood fibers for the first runs. Stock consistency was controlled by adding pulp sheets or water to the pulper. Stock was pumped directly from the pulper to the former. The stock flows, input to the former and bypass back to the pulper, are measured with magnetic flow meters. The difference in these two flow rates is the thick stock flow rate to the wire. The input flow rate to the former, determined from the flow meter output, is held constant by an automatic control valve which is operated by a pneumatic controller. During a run the static pressure in the former manifold, the input flow rate, and the bypass flow rate are monitored and recorded in the log book.

For a typical high consistency run, vacuum is only required in the slice suction box and one of the flat boxes. The data from a typical run (12B) are indicated on the next page.

Machine Speed	450 FPM
Wire Tension	30 PLI
Sheet Width	8"
Bone Dry Sheet Basis Weight	180 g/m ²
Dynamic Former:	
Manifold Pressure	9.0 PSIG
Input flow rate	48.6 GPM
Bypass flow rate	2.3 GPM
Sheet thickness at slice exit	0.180"
Vacuum levels	
Slice Suction box	
Compartment 1	0" water column
Compartment 2	12" " "
Compartment 3	5" " "
Compartment 4	5" " "
#1 Drainage Control Unit	0 " "
#2 " "	0 " "
#3 " "	0 " "
#1 Flat Box	0" Mercury
#2 "	0 "
#3 "	7" "
#4 "	0 "
Measured Consistency	(% Solids)
Stock Sample	3%
After former slice	3.2%
After slice suction box	5.7%
After last flatbox	17.6%
Run 12 B June 7, 1979	

Sheet samples are collected by hand after the last flat box. The samples have sufficient strength that they can be transferred to a table for storage after the run. The samples can then be used for pressing studies, or dried for strength tests, permeability work, and basis weight determination.

Figure 7.5 shows the dynamic former in operation with the sheet blown up in the air ready for collection at the end of the table.

7.4 The High Consistency Headbox for Low Speed Operation

The existing Lodding headbox for experimental forming at high consistency was designed to operate in the machine speed range 1200 to 1500 ft/min. It was not suitable for operation much below 1000 ft/min. and it was, therefore, necessary to design a new headbox for the low speed operation envisaged for the dynamic former. The energy dissipation level of the high speed headbox was used as the design point for the low speed configuration.

7.4.1 General Design Features of High Consistency Forming

Some of the general features of forming at high consistency which have a strong influence on headbox design include:

- a) High levels of turbulence both in magnitude and density are required to produce adequate floc breaking energy.
- b) The internal channel dimensions are small compared with those for a low consistency headbox operating at the same sheet basis weight. This is illustrated in figure 7.6 where a vertical dimension representative of stock depth, web thickness or slice opening is shown to scale for various stock consistencies. The high consistency headbox is, therefore, much more compact but manufacturing tolerances become much more acute. For low basis weight sheets such as tissue the stock depth and channel dimensions become very small. A wider range of stock depths is shown in figure 7.7 as a function of consistency and basis weight.

- c) For a web laid on a Fourdrinier wire at 2 to 4% consistency, little drainage can be expected from gravity, foil or table roll action. The headbox would be located at a position just upstream of the vacuum assisted drainage devices such as suction boxes. The table length would be one-third to one quarter of that required for forming at low consistency.

The broad design philosophy for the high consistency headbox consists of:

- a) Cross machine stock delivery to obtain uniform distributions of both stock and consistency.
- b) A high concentration of shear and/or turbulence to break the flocs, recognizing that total hydraulic pressure drop is not a complete measure of floc breaking capacity.
- c) A minimum dwell time after floc breaking, subject to smoothing out transverse flows and large scale eddies, and stilling the turbulence.
- d) Adequate pressure gradient at all stages from manifold to slice exit, to ensure control of flow through the headbox.

There are two main groups of devices for introducing the floc breaking energy:

1. Hydraulic head loss elements in the headbox, with energy supplied by the stock supply or fan pump.
2. "Externally" supplied energy using independent sources such as mechanical rolls, paddles or agitators, very high pressure water jets, vibration, acoustic excitation, etc.

The second group has the advantage that the floc breaking energy supply can be made independent of the stock consistency, basis weight and volume flow rate. However, there is considerable extra complexity and the transfer of energy may not be accomplished with high efficiency.

There are several devices which fall into the first group. Modern headboxes working at conventional consistencies employ turbulent pipe flow, step diffusors, explosion chambers and labyrinths to induce turbulence of suitable scale and intensity to produce a uniform stock suspension at the slice. These devices do not have a sufficiently high specific energy dissipation, i.e. energy per unit volume of stock, to be useful for high consistency forming.

A selection of hydraulic loss elements suitable for high consistency forming have been conceived and tested for comparison purposes.

These include:

1. A device to impart energy to the flow through swirl.
2. Miter bends.
3. Interacting shear flows with single and triple interfaces.
4. Orifices.

The first device has a low energy dissipation and the ordered nature of the flow can produce streaks in the final discharge. A 90° miter bend has a head loss coefficient which is a function of effective radius and has a maximum value of about 1.8. The advantage of the miter bend is that it has only a small separation and stagnation region, where flocs can reform. However, the secondary flows in the bend are a potential source of streaking. By suitable orientation of interacting flows, large shear and turbulence can be generated which will minimize

the streaking potential of the pure shear flow. Combinations of miter bends and shear flows have produced head loss coefficients ranging from 1.7 to in excess of 3. Most of the data base for elements 1-3 was developed during the earlier high speed headbox studies.

A sharp edged orifice has a head loss coefficient which can be as high as 2.7. It is an attractive floc breaking device because of the rapid axial accelerations that occur in the inlet region and because the head loss is converted almost entirely to velocity head. By impacting the orifice flow on a solid surface, this velocity head can be converted, in a small volume, to a heavy shear. In practice, to keep the fiber transit time reasonably short downstream of the shear, a fluid velocity similar to the machine speed is required and some kinetic energy recovery will therefore result. Also, three dimensional shear flows exist and these can produce undesirable vortex flows and stagnation zones. The sharp edged orifice was chosen for the low speed headbox design. Scaling and geometry optimization of the element are considered in the next two sections and the complete headbox design is described in the last section.

7.4.2 Speed Scaling For High Consistency Headboxes

To demonstrate the design process for the low speed headbox, a simple scaling argument is used. This shows that by suitable internal dimensioning the same energy density can be achieved at low and high machine speeds. It is assumed that the floc breaking element has an effectively circular cross section with an equivalent diameter, d , which can be varied for design purposes. The following variables are introduced:

- Q = stock volume flow rate per unit machine width
 U = machine speed
 V = stock velocity through the floc breaking element
 d = effective diameter of the floc breaking element
 N = number of floc breaking elements per unit machine width
 ΔP = hydraulic pressure drop
 E = energy dissipation
 e = energy dissipation per unit volume

These quantities have the following proportional relationships:

$$Q \propto U$$

$$NVd^2 \propto Q$$

$$V^2 \propto \Delta P$$

$$E \propto \Delta PV$$

$$e \propto E/d^2$$

They can be combined to give:

$$e \propto U^3/d^8 N^3$$

For the same energy density e , the effective diameter of the floc breaking element has to scale with machine speed U as:

$$d \propto (U/N)^{3/8}$$

A single hole of 0.75 inch diameter which is an efficient floc breaker at a machine speed of 1200 ft/min. would have to be reduced to 0.497 inch diameter for a machine speed of 400 ft./min. A practical limit to the amount of hole size reduction is imposed by the increasing tendency to plug with stock.

7.4.3 The Floc Breaking Element

A series of hydraulic tests were carried out on the basic floc breaking element used for the low speed headbox. The geometry of the element is shown diagrammatically in figure 7.8. The figure also shows some of the dimensional quantities that were varied to optimize pressure loss and uniformity of exit flow. The flow enters from the cross machine header and is accelerated through the orifice. The resultant jet impacts on the bottom wall to produce high shears and turbulent flows. The back face of the cavity is contoured to straighten the mean flow at the exit. Elements were tested singly in a recirculating tank facility using plain water as the medium for convenience. Previous tests with elements of a similar type had shown that the presence of fibers in the flow had little effect on pressure losses even at consistencies in the range 2 to 3%. Fiber concentration appears to have a more important effect in increasing turbulence decay and in pipe flow resistance,

The quantities measured were mean velocity, static pressures and exit total head distributions, and a certain amount of flow visualization was carried out. The latter is very difficult to achieve with success in flows of this type because of the deliberately high turbulence levels. Conventional visualization techniques are best suited to steady ordered flows. However, it was possible to observe features such as stagnation regions and significant mean cross flows. The test rig is shown in figure 7.9.

The following parameters and variables in the element shown in figure 7.8 were tested:

<u>PARAMETER</u>	<u>NUMBER OF CONFIGURATIONS TESTED</u>
Orifice diameter	3
Orifice shape	3
Cavity depth	3
Cavity shape	3
Orifice location	5
Exit shape	1

The variation of static pressure loss in the test element is plotted as a function of mean exit velocity in figure 7.10. The pressure drop has been corrected for inlet and exit dynamic heads and the variation follows an approximately square law relationship. The headbox design is such that the exit velocity from the element is approximately equal to the wire or machine speed so that the stock flow is not substantially accelerated or decelerated once it has left the floc breaking region. For design purposes the pressure loss ΔP was non-dimensionalized into a loss coefficient C_d using a dynamic head based on orifice velocity V rather than the exit velocity. This is expressed as

$$\Delta P = C_d \frac{1}{2} \rho_w V^2$$

A typical plot of C_d is shown in figure 7.11. For most purposes it can be assumed that C_d has a constant value over the operating range of exit velocities. In addition, it was found that, for sharp edged orifices, C_d was independent of the orifice diameter. As the cavity depth below the orifice is reduced the static back pressure in the jet builds up and the head loss and loss coefficient both reduce. This is illustrated in figure 7.12.

The flow uniformity at the exit can be controlled by the location of the orifice centerline in relation to the cavity geometry. Figure 7.13

shows that, if the orifice edge is separated from the cavity back wall (top figure (a)), the flow velocity peaks at the sides of the exit channel. The variation in velocity may be as much as 40% of the mean velocity. The velocity distribution was measured by the total head probe shown in figure 7.9.

When the orifice partially overlaps the back wall of the cavity as in (c) of figure 7.13, the velocity peaks in the middle of the channel with variations of 35% on the mean value. At the intermediate position where the orifice and back wall meet tangentially as shown in (b) of figure 7.13, the exit flow has the most uniform distribution with a maximum variation of 12% about the mean flow value.

The results of these various investigations were used for the headbox scaling and design described in the next section.

7.4.4 The Low Speed High Consistency Headbox Design

The scaling and design quantities used were:

- a. Wire or machine speed
- b. Required head loss
- c. Sheet basis weight
- d. Stock consistency
- e. Orifice diameter
- f. Orifice spacing
- g. Minimum allowable internal clearances
- h. Flow uniformity

The hydraulic performance characteristics of the low speed headbox are compared in the following table with the existing Lodding high speed headbox. An important feature of the latter design is the ability to bypass part of stock flow after it has left the floc breaking region, with the remainder exiting through the slice. In this way, a larger

pressure drop can be developed than without bypass and to some extent the floc breaking energy can be controlled independently of the machine speed. Up to about 50% of the total flow can be bypassed with the existing Lodding high speed headbox. Due to the inherent low total head downstream of the active elements, it is impractical to incorporate this principle in the low speed headbox.

	High Speed		Low Speed	
Machine Speed (ft/min)	1200		400	
Flow rate (gal/min) per foot of slice width (based on 2½% consistency and 40 lb/1000 ft ² basis weight)	231		76.8	
Headbox width (in)	24		8	
Number of holes across width	16		4	
Hole diameter (in)	0.754 (effective)		0.5	0.375
Hole area (in ²)	0.446		0.196	0.110
Head loss coefficient for each hole	1.7		2.1	2.1
Bypass ratio (bypass flow/slice flow)	0.5	0.7	0	0
Hole velocity (ft/sec)	31.2	35.4	21.0	37.3
Head loss (lb/in. ²)	11.1	14.3	6.23	19.7

The table shows that orifice diameters can be chosen for the low speed headbox which will produce equivalent pressure drops and energy density levels, without excessive risk of the holes plugging and without using a bypass flow after the floc breaking region.

The headbox configuration is represented diagrammatically in figure 7.14. This shows a manifold for the stock supply which is

tapered for inlet pressure uniformity. The stock flows from the manifold through the sharp edged orifices into the cavities which distribute the flow into the machine direction. Eddies, cross flows and turbulence decay in the stilling section before the stock reaches the slice. The slice is comprised of an upper solid, but adjustable top plate and the moving wire at the bottom. In order to relieve the shear on the stock in the slice between the moving wire on the bottom and the top stationary plate, a water layer is injected at the upper interface. This reduces the stock consistency slightly, but enables the stock to emerge at the machine speed. Compartmentalized suction is provided under the slice and the design combines this suction with a slice taper such that the stock leaves the stilling section at a consistency of $2\frac{1}{2}\%$ and the slice at 5% consistency. The mean flow velocity through the stilling section and under the slice is close to the wire speed. The stilling section has a slight taper from top to bottom which results in a constant static pressure down this vertical leg at the design speed. This is to prevent any flow separation due to adverse pressure gradient. The resultant difference in velocity between the top and bottom is about 6% .

The headbox is constructed largely of Plexiglas as an aid to flow visualization and the overall dimensions are 8 inches wide, 7 inches high and $12\frac{1}{2}$ inches in the machine direction. The headbox is shown in figure 7.15 mounted and in operation on the dynamic former.

A series of 33 machine runs were carried out in the Phase I period of the contract using bleached and unbleached kraft pulp. These investigated a range of stock consistencies from 1.6 to 3.4% , basis weights from 111 to 355 g/m^2 and machine speeds from 335 to 505 ft/min.

Headbox parameters and slice suction distributions were varied in order to determine those which have the most effect on sheet formation. The run details are presented in the following table:

TABLE OF HIGH CONSISTENCY TRAILS

<u>Run</u>	<u>Date</u>	<u>Stock Type</u>	<u>Stock Consistency (%)</u>	<u>Machine Speed fpm</u>	<u>Dry Basis Weight g/m²</u>
1	4/26/79	Unbleached Kraft Pulp	1.6	400	144
2	"	"	1.2	335	111
3A	4/27/79	"	2.4	335	268
3B	"	"	--	400	184
3C	"	"	--	505	165
4A	"	"	2.0	400	185
4B	"	"	--	505	159
4C	"	"	--	335	224
5A	5/2/79	"	2.5	400	244
5B	"	"	2.4	"	200
5C	"	"	2.4	"	169
6A	"	"	2.0	"	144
6B	"	"	2.1	"	178
6C	"	"	2.1	"	200
6D	"	"	2.1	"	183
6E	"	"	1.8	"	182
6F	"	"	2.3	"	213
7A	5/9/79	"	3.4	"	283
7B	"	"	--	"	--
7C	"	"	3.1	"	299
7D	"	"	3.4	"	355
8A	5/11/79	"	1.8	500	185
8B	"	"	1.8	"	173
8C	"	"	1.8	"	211
8D	"	"	1.8	"	193
9A	5/15/79	Bleached Kraft Pulp	2.4	336	258
9B	"	"	2.2	500	220
9C	"	"	2.2	500	245
10A	5/21/79	"	2.8	450	220
10B	"	"	3.0	450	250
11A	5/24/79	"	2.6	335	220
11B	"	"	2.3	335	215
11C	"	"	1.8	385	170

Throughout the course of Phase I, it became increasingly apparent that increased permeability is the major factor governing the energy savings associated with high consistency forming. On each section of the paper machine; wet end, press, and dryer, the increased permeability of the high consistency sheet leads to energy savings (see sections 4, 5 and 6). As this became apparent, the emphasis of the measurements on sheet properties centered on permeability techniques. Section 7.5.1 introduces the basic concepts governing permeability of porous compressible mats such as paper. The subsequent two sections, 7.5.2 and 7.5.3, describe the experiments which were conducted with water and air respectively. The air permeability technique described in section 7.5.3 is a relatively simple procedure and preliminary work indicates that the permeability of sheets formed at high consistency is almost twice that of equivalent low consistency sheets.

7.5.1 Permeability of Porour Compressible Mats

There is a large body of literature (References 4, 19-24) on the permeability of compressible mats. On a paper machine the interest centers around the hydrostatic driving force ΔP_h , required to produce a given flow rate through the mat. With the exception of initial wet end drainage, the flow rates and fluid velocities on a paper machine are so low that viscous rather than inertia forces control the fluid behavior, while surface tension and mechanically or thermally induced pressure gradients are more important than gravitation effects.

The following discussion is restricted to the flow regime where viscous forces are dominant and gravitational forces can be ignored.

The porosity, ϵ , of the mat is defined as the volume fraction of the mat which is filled with the permeating fluid (water or air on a paper machine). Mat porosity is often used as the independent variable when scaling permeability data. For mats of wood fibers, the porosity can be related to other sheet properties: fiber concentration ζ , moisture/fiber ratio m , and sheet solids content c , as follows:

$$\epsilon = 1 - \zeta / \rho_f = \frac{m}{m + \rho_w / \rho_f} = \frac{1 - c}{1 - c + c \rho_w / \rho_f} \quad \text{Equation (7.1)}$$

In steady flow through an incompressible mat, the superficial velocity, $\bar{w}$, is defined as the flow through the plan of the sheet divided by the area through which the flow is taking place. Note that the mean velocity, w , of the fluid in the mat is greater than the superficial velocity, because the flow only takes place in the void spaces between fibers.

$$w = \bar{w} / \epsilon \quad \text{Equation (7.2)}$$

For the flow regime defined above, the superficial velocity, $\bar{w}$, is related to the pressure drop across the mat by Darcy's law:

$$\bar{w} = \frac{K}{\mu} \frac{\Delta P}{z} \quad \text{Equation (7.3)}$$

where K is the specific permeability of the mat, μ is the fluid viscosity, and z is the thickness of the mat.

The Kozeny-Carman model (Reference 20) is often used to relate the specific permeability, K , to properties of the solid material in the mat. To accomplish this, the effective pore size of the channels the permeating fluid passes through is calculated based on the surface area of solid material exposed to the flow. The pressure drop is calculated assuming viscous drag at the mean fluid velocity, w . The specific surface area, S_o , can be measured directly (Reference 21); but for fibrous mats like paper, where the fiber lengths are much greater than the circumference, the specific surface area can be estimated with equation 7.4.

$$S_o \cong \frac{4}{d_f} (1-\epsilon) \quad \text{Equation (7.4)}$$

here d_f is the effective fiber diameter.

The Kozeny-Carman expression for the specific permeability can be written as follows:

$$K = \frac{\epsilon^3}{k S_o^2} \cong \frac{d_f^2 \epsilon^3}{16k (1-\epsilon)^2} \quad \text{Equation (7.5)}$$

where k is the Kozeny factor. For porosities less than $1/2$ ($\epsilon < 0.5$), k is nearly constant with a value on the order of five ($k \cong 5$). In this porosity range equation 7.5, is very useful for cylindrical fibers as it gives a direct correlation between fiber diameter, mat porosity, and the specific mat permeability, K .

However, at higher porosities ($\epsilon > 0.5$) the Kozeny factor is itself strongly dependant on mat porosity. Several empirical correlations between k and ϵ have been developed. Carroll's correlation (reference 4) given in equation (7.6) is typical.

$$k = 5.0 + \exp [14(\epsilon - 0.80)]$$

Equation (7.6)

The following table lists typical sheet consistencies found in the press section, and the corresponding values of porosity ϵ (from equation 7.1) and the empirical Kozeny factor, k , (from equation 7.6). The fiber concentrations, ζ , corresponding to the indicated sheet consistency, c , are also shown in the table for $\rho_f = 1.6$. Note that in the range of interest, there is a significant variation in the Kozeny factor, k . Typical values of the specific permeability, K , have also been calculated from equation (7.5) assuming an effective fiber diameter of $d_f = 0.004$ cm.

Since wood fiber mats are compressible, the porosity of a mat can be controlled by the compacting pressure applied to the mat. Specific permeability for a wood fiber mat can only be determined if the flow rate through the mat is sufficiently low that the hydrostatic pressure drop across the mat is small enough that there is no significant variation in porosity through the sheet. To determine specific permeability, the flow rate, hydrostatic pressure drop, and porosity for a sheet of known basis weight must be measured simultaneously. A detailed description of an apparatus to perform this type of experiment is given by Grace (Reference 24).

Several investigators have conducted "constant rate filtration experiments" (Reference 22,23). Flow rate and pressure drop are monitored simultaneously as fibers are deposited on a screen. The data can be correlated to give useful relationships between the measured variables. However, in an experiment of this nature, the mat thickness is not known and porosity gradients exist in the test mats hence the specific permeability cannot be determined directly.

Sheet consistency c (dimensionless)	0.1	0.2	0.3	0.4	0.5	0.6
Porosity, ϵ (dimensionless) from Equation (7.1)	.935	.865	.789	.706	.615	.516
Kozeny factor, k (dimensionless) 11.63 from Equation (7.6)		7.48	5.85	5.27	5.08	5.02
Specific Permeability K (cm^2) from Equation (7.5) assuming $d_f = .004$ cm	1.67×10^{-5}	4.74×10^{-6}	1.88×10^{-6}	7.72×10^{-7}	3.10×10^{-7}	1.17×10^{-7}
Fiber concentration, ζ (g/cm^3) from Equation (7.1) assuming mat is saturated with water	.104	.216	.338	.471	.615	.774

In the following sections, tests which are based on both these techniques are described. Using air as the permeating fluid has proved to be the most successful method for determining specific permeability. A variation of the constant rate filtration procedure has also been conducted using water.

In both series of experiments, it was found easiest to correlate the data in terms of the specific permeability, K , and the fiber concentration, ζ . The specific permeability is a single valued function of the fiber concentration. Over limited ranges the dependence can be modeled as a power law relationship, where A and B are empirical constants

$$K = A\zeta^B \quad \text{Equation (7.7)}$$

7.5.2 Water as the Permeating Fluid

A simple permeability cell shown in Figure 7.16 which can be used to measure the permeability of sheet samples to water or air was constructed. The sheet sample is clamped between two plates covering a 1-1/16" diameter orifice. The downstream side of the sheet is backed by a fine mesh bronze screen. Water or air is forced through the sheet, and the pressure drop across the sheet is measured as a function of the flow rate through the sheet. This data can be used with equation (7.3) to find the specific permeability, K , as a function of fiber concentration, ζ .

The initial experimentation was conducted with water as it is the permeating fluid in the press section.

The procedure used with water is similar to the constant rate filtration procedure described in the previous section, 7.5.1. The water supply for the test cell was filtered by a one micron filter cartridge before being forced through the paper sample. In the final configuration, the water was supplied from below the sheet in such a manner that both the bottom and top surfaces of the sheet were immersed in the water. This eliminated the surface tension effects which were appreciable when the downstream sheet surface was exposed to air and water simultaneously. The water temperature was monitored to account for changes in the absolute viscosity of the water. The upstream side of the paper sample was covered with a piece of filter paper which served two purposes: (1) It kept the upstream surface of the sheet from being disturbed by the flow and (2) it applied a compressive load, P_1 , to the upstream side of the sample. The compressive pressure on the downstream side is equal to the hydraulic pressure on the supply side of the assembly and was monitored with a pressure gauge.

Figure 7.17 shows the results of two permeability tests conducted on the same sample. With the filter paper and paper sample both in place, the first run was made on a freshly made low consistency hand sheet by slowly increasing the supply pressure and then reducing it again while monitoring the flow rate. The sheet was left immersed in the water, with no through flow for five minutes and then a second run was made the same way. The arrows on the lines connecting the data points indicate the order in which the measurements were made (increasing or decreasing pressure). The paper sample was then removed and the supply pressure versus flow rate was monitored

with the filter paper in the permeability cell by itself. In this case, the supply pressure is equal to the compressive pressure, P_1 , exerted by the filter paper on the upstream side of the paper sample. The filter paper was designed for wet filtration work and in an independent test it was found to exhibit the behavior shown in figure 7.17. i.e. it was not affected by the number of compressive cycles it had been subjected to. In figure 7.17 the flow rate has been converted to the superficial velocity, $\bar{w}$, by dividing the flow rate by the surface area of the orifice, and the pressures are shown in dynes/cm².

The "S" shape at the beginning of the first compression curve is not understood, although it could be caused by small air bubbles initially trapped in the wet paper sample when it was transferred to the permeability cell. The rest of the data points follow the behavior predicted by equations 7.3 - 7.6.

It is interesting to note that the supply pressure required to produce a given velocity, $\bar{w}$, is higher during equivalent portions (increasing or decreasing pressure region) of the second compression, presumably because the fibers have deformed during the first compression run and the fiber densities are higher during the second run. However, the pressure required to produce equal velocities, $\bar{w}$, is higher during the last half of the first run where pressure is decreasing than it is during the first half of the second run, where the pressure is increasing. This suggests that the fibers had some elastic recovery between the end of the first run and the beginning of second. The two curves indicate that the rate of compression and decompression was affecting the fiber concentration, ζ , in the same manner as the number of compressive

cycles affected fiber density in the static compression tests described in Section 7.13.

Figure 7.18 shows that the initial "S" shape can be eliminated by starting the run at a high pressure and monitoring the flow rate as the pressure is slowly reduced. This procedure only uses the data from the last half of the curves shown in figure 7.17. The water permeability procedure could be used to make relative comparisons between high and low consistency sheets. However, it does not give a direct measure of the sheet permeability, but rather a combined measure of the compression response and permeability of the sample. To uncouple these two effects, experiments using air as the permeating fluid were conducted.

The most important result obtained from the permeability experiments with water is that the initial compressive response of the wood fiber mats is strongly dependant on previous compressive history. To perform accurate pressing or permeability experiments, the previous history must either be repeated precisely for each experiment or eliminated as a dependant variable.

7.5.3 Air As The Permeating Fluid

Samples of the wet mat samples were dried between two press plates constructed so that the mat thickness could be controlled before the sheet was dried. Some shrinkage occurred during the drying process, but the thickness and basis weight of the dry sample were measured after the samples were dry. In this way, a dry sheet of uniform fiber density was formed. The dry fibers have sufficient

rigidity that the mats are incompressible at the low supply pressures required for air permeability measurements. Since the fiber concentration ζ , is determined directly from the observed basis weight and sheet thickness, the compressive response of the fibers is not required to determine the specific permeability.

The dry samples are placed in the permeability cell and clean, dry air is forced through the sample. The air flow rate is measured as a function of the pressure drop across the sample. The superficial velocity through the mat, $\bar{w}$, is calculated by dividing the flow rate by the cross-sectional area of the orifice. Figure 7.19 shows typical data for three bleached kraft handsheets formed at low consistency. As the sheets are incompressible, the superficial velocity $\bar{w}$, is directly proportional to pressure drop. The constant of proportionality is the specific permeability, K , divided by the product of the sheet thickness, z , and the absolute viscosity of the air, μ , (see equation (7.3))

The viscosity of the air was obtained from published data on the variation of viscosity with temperature (no correction for absolute pressure was used as the applied pressures were nearly atmospheric).

As there are small variations in the calculated value for the specific permeability of different pieces of the same sample at fixed fiber concentration, at least six samples were tested to determine the mean value of K for each fiber concentration, ζ . The specific permeability appears to be independent of basis weight for the range of basis weights tested $0.01 < b < 0.03 \text{ g/cm}^2$. Figure 7.20 shows the relationship between specific permeability, K , and fiber concentration, ζ , for bleached kraft handsheets formed at low consistency. The error brackets represent the standard deviation about the mean value of K for samples which had the same fiber concentration. The data will fit the power law relationship

(equation (7.7) over the range $.2 < \zeta < .6$ with $A = 1.08 \times 10^{-10}$ and $B = -4.243$.

For comparison a dynamically formed high consistency bleached kraft sample was also tested. To minimize any basis weight nonuniformity, two sheets samples were pressed together before drying to make a test sheet with a basis weight of $b \approx 0.035 \text{ g/cm}^2$. By sandwiching two sheets together the random basis weight variations in each sheet tend to cancel each other and the effect of formation on the specific permeability is minimized. The fiber concentration of the high consistency sample was $\zeta = 0.50$; the specific permeability was found to be $K = 3.6 \times 10^{-9} \text{ cm}^2$. This is 80% greater than the permeability obtained from figure 7.20 for a low consistency handsheet at the same fiber density. Permeability differences of this order suggest it will be significantly easier to remove water from a high consistency sheet in the press section than a low consistency sheet.

Figure 7.1 Handsheet Former

7.2. Static Compressive Response of Handsheets

Figure 7.3. Dynamic Forming Concepts

Figure 7.3. Dynamic Forming Concepts

e.

f.

g.

Figure 7.4 Schematic of Dynamic Former Table

Figure 7.5 Dynamic Former in Operation

Figure 7.6. Stock Depth as a Function of Consistency.

Figure 7.7 Web Thickness as a Function of Consistency and Basis Weight

Figure 7.8 Floc Breaking Element Geometry

Figure 7.9 Floc Breaking Element Under Test

Figure 7.10 Pressure Loss Variation with Exit Velocity

Figure 7.11 Non-dimensional Loss Coefficient

Figure 7.12. Effect of Cavity Depth on Loss Coefficient

Figure 7.13 Fluid Velocity Distributions at Element Exit

Figure 7.14. High Consistency Low Speed Headbox.

Figure 7.15 High Consistency Headbox in Low Speed Operation

Figure 7.16 Permeability Cell

Figure 7.17 Water Permeability Measurements

Sample 4A

Basis Weight $.022 \text{ g/cm}^2$

Pressure Drop
Across
Sample
(dynes/cm²)

Figure 7.18 Water Permeability Measurements

Sample 4B

Basis Weight .022 g/cm²

Pressure Drop
Across
Samples

(dynes/cm²)

- o 1st Compression: Sample and Filter Paper
- x 2nd Compression: Sample and Filter Paper
- Filter Paper alone

Superficial Flow Velocity $\bar{w}$ (cm/sec)

Figure 7.19 Air Permeability Measurements

Pressure Drop
Across
Sample P
(dynes/cm²)

Figure 7.20 Bleach Stock Specific Permeability
Measured with Air

8. CONCLUSIONS

The major achievements for Phase I. of the contract may be summarized as follows:

1. The development of theoretical models of water removal and energy consumption to show where high consistency forming offers energy savings.
2. Completion of a comprehensive survey of U.S. pilot paper machines and discussion of the case for a centralized test facility, leading to the conclusion that the Department of Energy should not support such a facility at this time.
3. The construction of a moving wire type dynamic former and associated stock delivery system for high consistency sheet forming development work.
4. The development of a prototype high consistency headbox for operation at low machine speeds on the dynamic former.
5. The fabrication and operation of test equipment for the measurement of sheet drainage properties such as permeability.
6. The determination of special experimental equipment and techniques to demonstrate the effect of high consistency forming on water removal.
7. The formation and initial testing of sheets from high consistency stock.

These achievements can be built on during Phase II in order to meet the two specific aims of:

- a. Demonstrating the energy savings of high consistency sheets through increased permeability and the improved pressing efficiency which results.
- b. Carrying out development work on the headbox necessary for the production of sample sheets with the correct structural and formation characteristics for use in (a).

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10. LIST OF SYMBOLS

A, B	Empirical constant used in equation (7.7).
$b, \Delta b$	Sheet basis weight and incremental change in basis weight respectively.
c	Sheet solids content or consistency.
$c_o, \Delta c_o$	Sheet consistency at entry to the dryer section and incremental change in this consistency respectively.
c_c	Sheet consistency at end of constant drying rate region.
$c_e, \Delta c_e$	Sheet consistency at the dryer section exit and incremental change in this consistency respectively.
C_d	Non-dimensional pressure loss coefficient.
d	Diameter.
d_f	Effective fiber diameter.
D	Roll diameter.
e	Turbulent energy dissipation per unit volume.
E	Turbulent energy dissipation.
k	Kozeny factor.
K	Specific permeability.
m	Moisture/fiber ratio.
M	Empirical constant used in equation (5.2).
n	Empirical constant used in equation (5.2).
N'	Number of floc breaking elements per unit machine width.
P'	Press nip lineal loading.
P_s	Compressive pressure.
P_l	Compressive load.
$P(x)$	Pressure distribution through the press nip.
P_{max}	Maximum pressure, at mid-nip of the press.
ΔP	Hydraulic pressure drop.

ΔP_h	Hydrostatic driving force.
Q	Stock volume flow rate per unit machine width.
r	Local drying rate for the sheet in mass of water per unit area per unit time.
r_p	Maximum pressure in the nip divided by the time required to reach this pressure.
R	Value of the drying rate in the constant rate region.
$S, \Delta S$	Steam consumption rate and incremental change in this rate respectively.
S_o	Specific surface area.
t	Time.
Δt	Time to reach maximum pressure in the press nip.
$U, \Delta U$	Machine speed and incremental change in speed respectively.
V	Flow velocity through the floc breaking element.
$\bar{w}, w$	Superficial and actual velocities of flow through the porous web.
x	Distance measured in the machine direction.
Δx	One half of the press nip width.
z	Uncompressed thickness of sheet plus felt.
Δz	Maximum change of sheet plus felt thickness in the press nip.
ϵ	Mat porosity.
μ	Fluid viscosity.
ρ_w	Mass density of water.
ρ_f	Mass density of wood fiber.
τ	Non-dimensional distance or time from dryer section entry.
τ_e	Non-dimensional total length of sheet in the dryer section.

ζ	Fiber concentration.
ζ_s	Fiber concentration under static compression.
$\Delta\zeta$	Decrement in fiber concentration from its value under static compression, i.e. $\Delta\zeta = \zeta_s - \zeta$.

APPENDIX I

STATEMENT OF WORK UNDER PHASE I OF THE CONTRACT

The following tasks are to be undertaken in Phase I of the contract:

Task 1. Preparation of Research, Development, and Demonstration
Program Plan for Paper Forming

Perform a survey of representatives of the U.S. Paper Industry covering mill operations, machine and equipment suppliers and consulting engineering firms concerning energy saving opportunities in the formation of all grades of paper and paper board. This study should include, but not be limited to high consistency forming, dry forming, RAD-FOAM formation, twin wire forming, and multi-ply formation. It shall cover the following aspects of these forming processes:

- 1.1 Stock Preparation - screening, cleaning, beating and refining. Pulping, de-inking and disperging for secondary fiber utilization.
- 1.2 Stock Delivery and Web Formation - high consistency stock preparation and headbox delivery systems, wire configurations, and wire drainage.
- 1.3 Mechanical pressing - roll nip design, felts and felt conditioning, thermal showers, and suction rolls.
- 1.4 Drying - Heated drum systems, yankee cylinders, flat bed dryers, air flotation and through-flow

dryers, ventilation, and recuperation systems.

Based on the survey and consultations with U.S. Paper Industry representatives, prepare an RD and D program plan providing particular attention to the mutual interactions of energy conservation, product quality, and the financial implication of equipment and process changes in the mill. It is expected that involvement of the international paper industry will be achieved with the aid of the international Energy Agency, DOE, and direct industry contact. Information will be gathered primarily by direct contact between Thermo Electron personnel and industry representatives.

Task 2. Determination of Test Machine Specifications and Facility Design and Costing

A basic design layout of the Test Facility composed of stock preparation test loops, test machine, presses and drying section, together with auxiliary laboratories and test equipment, will be prepared to support the research programs identified under Task 1 above. Particular attention will be directed towards flexibility of operation and short downtimes. Machine operating specifications, such as speed and running time, will be critically reviewed to ensure that they encompass future experimental needs, such as twin wire configurations and novel press or dryer arrangements. The availability and suitability of existing pilot-scale paper-making machines such as the U.S.D.A. Forest Service machine at Madison, Wisconsin, will be investigated.

A final layout and machine design/modification will be established and detailed engineering and costing will be carried out to provide the total Test Facility funding requirements, cost disbursement and construction schedules.

Consideration will be given to the organizational and administrative structures for the facility so that quick and efficient dissemination of derived information can be ensured.

Task 3. Phase I Reporting Requirements

A presentation on Phase I activities will be made to Industrial Energy Conservation personnel in August 1978 which covers tasks 1, 2, 4, 5, and 6. A proposed RD and D program for possible follow-on phases, covering test facility requirements, development and testing needs, and activities leading to commercial demonstration, along with cost estimates and a schedule of accomplishment shall be included. A final printed report shall be prepared and delivered by January 31, 1979 which details the RD&D program plan recommendations, results of the phase I activities, the Test Facility design and layout, the funding requirements, cost disbursements and a schedule for the phase II and phase III activities as determined by tasks 1 and 2.

Task 4. High Consistency Head Box Development

During Phase I, fundamental investigations of the internal hydraulic design of headboxes and sheet delivery systems will be conducted. Trials will be made to form samples for subsequent static pressing in order to determine improvements

in press drainage. An existing Thermo Electron headbox will be modified to do this work. Records of laboratory work and testing results will be maintained. Evaluation of test results will be reported in the Final Technical Report.

Task 5. Instrumentation Development.

Instrumentation requirements will be determined for making critical measurements in the area of:

- Head box internal hydraulics,
- Stock landing, forming and draining processes.

Specific quantities to be measured are:

- Pressure and velocity distributions using surface pressure sensors and pitot-static probes,
- Turbulence intensity using pressure transducers,
- Limited measurements on flow and stock uniformity using photographic flow visualization methods.

Equipment to facilitate these measurements is either available or will be purchased, and will be structured to enable the effects of headbox configuration changes made during phase I, to be systematically recorded and analyzed.

Task 6. Support Experiments

Auxiliary experiments will be continued through Phase I to support the headbox design program. They will include:

- Hydraulic tests of headbox elements; e.g., determination of pressure and velocity fields in channels and miter bends,
- Drainage resistance measurements of the formed stock as a function of consistency.

Records of laboratory tests will be maintained and evaluation of test results will be included in the Final Technical Report.

It is recognized that the phase I activity associated with tasks 4, 5, and 6 is preliminary with the balance of the task activity completed during phases II and III if authorized.

APPENDIX II

PILOT PAPER MACHINE FOR A CENTRALIZED EXPERIMENTAL FACILITY

The material in this Appendix is a summary of work jointly undertaken by Lodding and engineers of the C.T. Main Company to establish specifications, preliminary design layout, cost estimates and energy monitoring instrumentation for a pilot paper machine.

SPECIFICATIONS & DESCRIPTION OF THE MACHINE

The experimental facility consists of a standard hydraulic headbox for low consistency operation, nonshaking type fourdrinier, press section, alternate dryer section configurations, wind-up/unwind devices, stock preparation and other associated equipment, support systems, instrumentation and buildings.

The paper machine will have a 24 inch wide wire, a design and balance speed of 4000 ft./min. and a table of length 30 feet with breast roll, couch roll, wire drive roll, set of wire return rolls, wire guide and stretch systems. Test paper sheets up to a basis weight of 60 lb./1000 sq. ft. will be produced. However, the initial operating condition is only 2000 ft./min. speed, 12 in. wide sheet, 40 lb./1000 sq. ft. basis weight, headbox consistency 2%, 15 minutes run time, minimum stock delivery rate of 480 gals./min. at 2% consistency, and a consistency off the couch of 20%.

The stock preparation system will be capable of handling the equivalent of 15,000 gals./day of stock at 2% consistency. It will comprise a 5 cubic meter pulper operated on a batch basis at about 6% consistency, with an agitated dump chest of 3,800 gal. capacity,

deflaker, screen, cleaners and agitated accepts chest also of 3,800 gal. capacity. Stock temperature would be controlled by steam addition in the pulper dump chest. White water tanks will be provided for extracted water and auxiliary stock storage. Stock will be delivered to the headbox through a fan pump.

The press section will consist of a three-nip transfer press, having no open draws until after the third nip in order to provide flexibility in making tests in the press area and to provide acceptable machine runability through the initial dryer section.

The dryer section was initially conceived in four alternate forms, as follows:

- A) Complete dryer section for 40 lb. per 1000 sq. ft. at 2000 FPM operation. This required 75 dryers.
- B) Partial dryer section consisting of 37 dryers or 49.3% of full dryer capacity required for 2000 FPM.
- C) Partial dryer section consisting of 13 dryers or 17.3% of full dryer capacity required for 2000 FPM. To this alternate, a windup/unwind device was added between the third press and the dryer to facilitate again passing the sheet through the dryer section for additional drying.

Of course, the ultimate sheet dryness in this arrangement could be achieved with one single repeat pass at a slow speed or multiple repetitive passes at higher speeds.

- D) Partial dryer section either as in B or C above, but off machine as opposed to on machine. This alternate provided substantially less operating flexibility, as well as reliability, while not providing discernible capital cost savings. While indeed the building configuration would be of more economical unit construction cost, it is also concluded that these savings

would be expended on machine auxiliaries, machine and building services and additional total building square foot area.

It is felt that the logical choices of drying alternates are - either a complete dryer section as in Alternate A or a flexible but partial on line dryer section as in Alternate C. Alternates B and D do not seem to have any recognizable redeeming features, while Alternate A offers some additional testing capability, but at a greatly increased cost over Alternate C. Consequently, estimates have been included for only Alternate A and C.

ADAPTATION TO INCORPORATE TWIN WIRE FORMING.

Replacement of the fourdrinier with a twin wire former, of the type where a free jet is discharged into the pocket between two converging wires, would require a complete replacement along with reorientation of the headbox. While it is likely that many of the wire rolls could be reused, there would be considerable auxiliary equipment required, new headbox supports, new former framing, special items, such as the Beloit Bel Baie shoe, or its counterpart, and other modifications.

A different approach than above, would be to add a top forming unit to the fourdrinier section. Such a top forming unit could be a Beloit Bel Bond, or similar device by other manufacturers. However, the characteristics of forming as opposed to just dewatering varies with the selection of top forming unit, and of course, all are different from the configurations with a free jet between converging wires mentioned earlier.

INSTRUMENTATION FOR MONITORING ENERGY CONSUMPTION

Instrumentation for monitoring energy consumption on the machine would be accomplished using electronic measurement transmitters feeding into a single or, perhaps, two multi-channel data loggers. Such an arrangement would provide a scanning type record of up to twenty separate channels with one channel to each measured quantity. These quantities may be electrical power measurements, steam pressures, steam flows, fluid quality or quantity, or air flows. The data loggers would be self-contained single tape recording devices not requiring any large instrumentation panels. The cost per channel to provide such a system is in the range of \$2,500 per channel, in groups of ten channels per roll chart. The costs for such instrumentation is not included in the various estimates for the facility presented herein.

Measurements envisioned are -

1. Stock Prep and Mach. Aux. Power
2. Refining Power
3. Vacuum Power Forming
4. Vacuum Power Presses
5. Machine Drive Total Power
6. Machine Drive - Selected Section or
Fan Pump Power
7. Machine Drive Voltage or Speed
8. Air Drying Systems Power
9. Steam Flow - Machine Total

10. Steam Flow - Selected Section -

such as: Fourdrinier

Shower Heating

Press Steam Shower

1st Dryer Section

2nd through Nth

Dryer Section

11. Pulp Stock Consistency

12. Pulp Stock Flow

13. Head Box Flow

14. Condensate Temperature

15. Condensate Flow

16. Flash Steam Flow/Pressure - Selected Point

17. Water Temperature - Selected Point

18. Water Flow - Selected Point

COST ESTIMATE SUMMARY

The cost estimates for the experimental facilities were prepared as for a full paper mill under the headings mechanical, electrical, piping, instrumentation and structural for both the paper machine and stock preparation system. For large items such as the fourdrinier table, quotations were obtained using the outline specifications. The summaries distinguish between the costs of equipment purchased from outside contractors and equipment that would be supplied by Thermo Electron as owner of the facility. The detailed cost itemization is not included here but the complete summaries of the cost estimates are presented under the following headings:

Test Paper Machine Less Dryers

Adaptation for Twin Wire Forming

Dryer Addition A

Dryer Addition C

ESTIMATE SUMMARY

Test Paper Machine Less Dryers

	<u>Owner Furnished</u>	<u>Contract Work</u>	<u>Total</u>
Site Preparation	\$ -	\$ 30,000	\$ 30,000
Structural	-	365,000	365,000
Paper Machine and Associated Equipment	765,000	105,000	870,000
Piping	60,000	75,000	135,000
Secondary Electric	45,000	85,000	130,000
Process Control	22,000	20,000	42,000
Heating and Ventilation	<u>19,000</u>	<u>16,000</u>	<u>35,000</u>
Sub Totals	\$911,000	\$696,000	\$1,607,000
Effluent Handling	56,000	36,000	92,000
Primary Power	11,000	14,000	<u>25,000</u>
Sub Total			\$1,724,000
Design Engineering			125,000
Field and Vendor Services Engineering			23,000
Contingency			<u>153,000</u>
TOTAL			\$2,025,000

ESTIMATE SUMMARY

Adaptation for Twin Wire Forming

	<u>Owner Furnished</u>	<u>Contract</u>	<u>Total</u>
Top forming Unit	\$125,000	\$30,000	\$155,000
Machine Supporting Facilities	<u>30,000</u>	<u>20,000</u>	<u>50,000</u>
Total	\$155,000	\$50,000	\$205,000
Engineering, Jobsite Services and Contingencies			<u>40,000</u>
Total			\$245,000

ESTIMATE SUMMARY

Dryer Addition "A"

	<u>Owner Furnished</u>	<u>Contract Work</u>	<u>Total</u>
Additional Structures	-	\$1,115,000	\$1,115,000
Additional Equipment With Associated Piping and Such Mechanical Components	\$2,752,000	590,000	3,342,000
Additional Secondary Electrical	33,000	6,000	39,000
Additional H&V	<u>7,000</u>	<u>5,000</u>	<u>12,000</u>
Total	\$2,792,000	\$1,716,000	\$4,508,000
Additional Design Engineering			350,000
Additional Jobsite Services			17,000
Additional Contingency			<u>100,000</u>
Additional Total			\$4,975,000

ESTIMATE SUMMARY

Dryer Addition "C"

	<u>Owner Furnished</u>	<u>Contract Work</u>	<u>Total</u>
Additional Structures		\$234,000	\$234,000
Additional Equipment With Associated Piping And Such Mechanical Components	\$657,000	168,000	825,000
Additional Security Elec.	20,000	4,000	24,000
Additional H & V	<u>5,000</u>	<u>3,000</u>	<u>8,000</u>
Total	\$682,000	\$409,000	\$1,091,000
Additional Design Engineering			120,000
Additional Jobsite Services			15,000
Additional Contingency			<u>90,000</u>
Additional Total			\$1,316,000

178
176

LONGITUDINAL SECTION
75 DRYERS
SCALE: 1"=10'-0"

PLOT PLAN
SCALE: 1"=50'-0"

REPORT	
NO. DATE	DESCRIPTION
DRAWN BY M. J. J. J. J.	CHECKED BY
DESIGN DATE SEP 15 1978	DESIGN TIME
PROJECTING DATE OCT 15 1978	PROJECTING TIME
PROJECTING NAME G. A. FLETT	
CHECKED BY B. E. CLARK	
<p>MAIN CHAR. T. MAIN, INC. <small>DESIGN & CONSTRUCTION ENGINEERS & ARCHITECTS</small></p>	
<p>CLIENT PROJECT TITLE LODDING A DIVISION OF THERMO ELECTRON CORPORATION</p>	
<p>PROJECT DESCRIPTION TEST PAPER MACHINE FACILITY</p>	
DATE	BY
PROJECT NO. 3247-6-0001	REV.

APPENDIX III

PILOT PAPER MACHINE SURVEY

A survey of pilot paper machines in the United States was conducted in two steps. An initial telephone survey was conducted to obtain basic information on the existing machines. This information was reviewed and a format was developed for summarizing the survey data so that the characteristics of the various facilities could be compared at a glance. This summarized data was then submitted to each responding institution for verification and permission to publish.

The questionnaire used for the basis of the telephone survey is shown on the next two pages. The verified, summarized data on pilot paper machines in the United States is shown on the remaining pages. The survey data is broken down into five major groups as follows: Foundations, Government Facilities, Universities, Paper Companies, and Equipment Suppliers.

It should be noted that the question asked in the initial survey was whether the facility would be: available for use by Lodding for research projects. In the final format, the emphasis changed to: available to any outside user, where "available" is defined as no policy restrictions other than scheduling limitations. Thus a facility may have unlimited availability as defined above, and yet have sufficient work scheduled that an outside user would not be allowed access. We apologize for any confusion this change in emphasis

and wording may have caused. The data presented reflects current policy at the institution indicated in 1979.

We would like to take this opportunity to thank each of the institutions and principal contacts for their time and cooperation in helping to complete this survey.

SURVEY OF TEST PAPER MACHINES

MILL
INSTITUTION _____
LOCATION _____

PAPER MACHINE TYPE		
MAKE		
PURPOSE OF TESTING		
WIDTH :	WET END	
	DRY END	
GRADES		
SPEED		
GRADES		
SPEED		
FURNISH		

STOCK PREPARATION :

STOCK CHEST CAPACITY	
STOCK CHEST CONSISTENCY	
MAX. TIME OF CONTINUOUS OPERATION	
REMARKS	

WET END :

HEAD BOX - TYPE	
FOURDRINIER	
OTHER ARRANGEMENT Cylinders, Former etc.	
CONSISTENCY MAX.	
INSTRUMENTATION	
PRESSES	
NUMBER - FORMATION	
INSTRUMENTATION	

DRY END :

DRYERS TYPE	
DIAMETER	
NUMBER	
OTHER : COATER, SIZE PRESS etc.	
INSTRUMENTATION	
CALENDERS - TYPE	
NUMBER OF ROLLS	
INSTRUMENTATION Profile . Moisture etc.	

OPERATION :

OPERATION :
How often is the machine used ?
Hrs of operation per day, week
POSSIBILITY OF USING THE MACHINE FOR PROJECTS BY LOADING R & D

SUMMARY :

[illegible]

SUMMARY
Survey of Pilot & Laboratory Paper Machines: Foundations

Test Facility & Location	Contact	#Type of Machine	Wet End width (inches)	Maximum Speed Capability (Fpm)	Additional Equipment				Available to Outside Users for Testing Purposes
					Press	Dryer	Yankee	Calendar	
Herty Foundation Savannah, GA	Dr. J. Robert Hart (912)964-5541	F	36"	300	3 Nips	12 Cans	No	Yes	Yes
		F	31"	75	2 Nips	9 Cans	1	Yes	Yes
		O**	28"	100	2 Nips	9 Cans	1	Yes	Yes
		F	10"	50	2 Nips	14 Cans	No	Yes	Yes
		**Sandy Hill Rotoformer Contract work conducted on a confidential basis							

* F (Fourdrinier), TW (Twin Wire), O (Other)

SUMMARY
Survey of Pilot & Laboratory Paper Machines: U.S. Government Facilities

Test Facility & Location	Contact *	*Type of Machine	Wet End width (inches)	Maximum Speed Capability (fpm)	Additional Equipment				Available to Outside Users for Testing Purposes
					Press	Dryer	Yankee	Calendar	
Forest Products Laboratory Madison, WI	Dorald Fahey (603) 257-2211	F	13"	Wet 325 Dry 125	3 Nips	15 Cans	None	5 Rolls 7 Rolls	Limited
	Machine capable of operating at 325 fpm. However, unable to form and dry because of limited drying capacity, paper or paperboard at a speed much above 125 fpm. Three wet presses and one smoothing press.								
U.S. Department of Agriculture Peoria, IL	Dr. Bernard T. Hoffeier (309) 685-4011	F	16" or 32"	Wet End 500 Dry End 500	3 Nips	17 Cans	None	6 Rolls	Limited
Nat'l. Bureau of Standards Industrial Bldg. Rm A 106 Washington D.C.	Mr. D. Fletcher (301) 921-3668	F	28"	100-125	Yes	Yes	None	Yes	Limited
		O	28"	100-125	Yes	Yes	Yes	Yes	Limited

*F (Fourdrinier), TW (Twin Wire), O (Other)

SUMMARY
Survey of Pilot & Laboratory Paper Machines: Universities

Test Facility & Location	Contact	Type of Machine	Wet End width (inches)	Maximum Speed Capability (fpm)	Additional Equipment				Available to Outside Users for Testing Purposes
					Press	Dryer	Yankee	Calendar	
Institute of Paper Chemistry Appleton, WI	Dr. T. S. Fox (414) 734-9251	F	18"	1000	None	None	None	None	Yes
University of Florida Gainesville, FLA	Professor Walker (904) 392-0884	F	6 1/2"	30	Very limited	None	None	None	Very limited Due to scheduling constraints.
University of Lowell Lowell, MA	Asst. Professor J.W. Walkinshaw (617) 454-7811	F	12"	20	1 Nip	Hot Air	None	OM 3 Rolls	Yes
University of Maine Orono, Me	Professor J.M. Genco (207) 581-7317	F	12"	200	2 Nips	16 Cans	None	OM 2 Rolls	Yes
		O	6"	10	1 Nip	None	None	None	Yes

*F (Fourdrinier), TW (Twin Wire), O (Other)

SUMMARY
Survey of Pilot & Laboratory Paper Machines: Universities

Test Facility & Location	Contact	#Type of Machine	Wet End width (inches)	Maximum Speed Capability (fpm)	Additional Equipment				Available to Outside Users for Testing Purposes
					Press	Dryer	Yankee	Calendar	
Miami University Oxford, OH	Dept. Chairman C. Edwin Brandon (513)529-3518	F Has a secondary head box	15"	60	2 Nips	27 Cans	18" Dia.	7 Rolls	Yes
State University of New York College of Envir. Science & Forestry Syracuse, NY 13210	Professor Ken Britt (315)473-8731	F	48"	230	2 Nips	18 Cans	None	8 Rolls	Yes
North Carolina State University Raleigh, NC	Professor R.G. Hitchings (319)737-2888	F	12"	100	2 Nips	13 Cans	None	5 Rolls	Yes
		F	12"	20	1 Nip				Not Operational
Western Michigan University Kalamazoo, MI	Rcct. Kinsey Carl F. Schuster (616)383-1802	F	27"	200	2 Nips	Yes			Yes
		0** **2 2	28" Sheet may be wound wet and dried on fourdrinier dryers. (very unusual) May be used to test pl-bonding on different stocks.	900	3 Nips	None	None	None	Yes

* F (Fourdrinier), TW (Twin Wire), O (Other)

SUMMARY

Survey of Pilot & Laboratory Paper Machines : Universities

[illegible]

* F (Fourdrinier), TW (Twin Wire), O (Other)

SUMMARY
Survey of Pilot & Laboratory Paper Machines: Paper Companies

Test Facility & Location	Contact	*Type of Machine	Wet End Width (inches)	Maximum Speed Capability (fpm)	Additional Equipment				Available to Outside Users for Testing Purposes
					Press	Dryer	Yankee	Calendar	
Brown Company Berlin, NH	Dr. R.H. Danforth (603) 752-4600	F	41"	175	2 Nips	13 Cans	60" Dia.	6 Rolls	Not Operational, for sale.
Crown Zellerbach Camas, WA	Dr. G.G. Vincent (206) 834-444	F	26"	250	2 Nips	Cans	Yes	4 Rolls	Limited, not generally available except to potential customers.
International Paper Tuxedo Park, NY	Dr. J.E. Luce (514) 351-2101	O	36"	250	1 Nip	Cans and infrared	None	None	Yes
Kimberly Clark Neenah, WI	Neil Springer (414) 729-1212		One Machine: Machine Information Proprietary						No
3M Corp. St. Paul, Mr.	Mike Gardner Lloyd Ficard, Dir. (612) 459-2339	F	26"	100	2 Nips	Cans	None	4 Rolls	No
Mead Corp. Chillicothe, OH	John R. Arnold (614) 772-3133	F	12"	15	2 Nips	18 Cans	One	1-3 Nip	Limited

*F (Fourdrinier), TW (Twin Wire), O (Other)

SUMMARY
Survey of Pilot & Laboratory Paper Machines: Paper Companies (continued)

Test Facility & Location	Contract	*Type of Machine	Wet End width (inches)	Maximum Speed Capability (fpm)	Additional Equipment				Available to Outside Users for Testing Purposes
					Press	Dryer	Yankee	Calendar	
Scott Paper Chester, PA	Quentin C. Weaver (215) 521-5000	Machine Information Proprietary							No
S.D. Warren Westbrook, ME	Robert Chamand Herb Connell, Director (207) 856-6311	F	22"	225	3 Nips	30 Cans	None	Yes	Very limited Each case considered separately.
Westvaco Corp. Covington VA	Dr. J. Glomb Dr. R. Brennan (703) 962-2111	F	25"	1700	2 Nips	None	None	None	Very limited.
Weyerhaeuser Federal Way	Dr. C.S. Walseth (206) 924-3332	F	12"	20	1 Nip	** Hot Air	None	None	Very limited. Only in case of cooperative studies of special interest to Weyerhaeuser.
					** 3 Steam cans ahead of hot air dryer incorporated as of 7/1/79.				

*F (Fourdrinier), TW (Twin Wire), O (Other)

SUMMARY
Survey of Pilot & Laboratory Paper Machines: Equipment Suppliers

Test Facility & Location	Contact	*Type of Machine	Wet End width (inches)	Maximum Speed Capability (fpm)	Additional Equipment				Available to Outside Users for Testing Purposes
					Press	Dryer	Yankee	Calendar	
Beloit Corporation Beloit, WI	Dave Gustafson (508) 365-3311	F	10"	500	None	None	None	None	Not operational
		TW	18"	4000	3 Nips	None	None	None	Yes
		TW	18" (Bond)	7000	3 Nips	None	None	None	Yes
Black Clawson Watertown, NY	Tom Patell Will Motbchm (315) 788-2004	TW	22"	3500	3 Nips	None	None	None	Limited Primarily for product development.
Huyck Corp. Rensselaer, NY	Frederick Smart (518) 445-2711	F	16"	3000	3 Nips	None	None	None	Limited Primarily for Internal Research.
Lodding Auburn, MA	Michael Judd (617) 791-8171	F	22"	400	None	None	None	None	Yes
Sandy Hill Corporation Hudson Falls, NY	Karl Kroetz (518) 747-3381	Inclined	8 "	1000	2 Nips	Thru Air** Dryer	Gas	1 Nip	Yes
		O +	8 "	1000	2 Nips	Yankee 8" Dryer	Gas	1 Nip	Yes
		+ Vacuum Former (Roto Former)			** Machine can be arranged such that the sheet can also be passed over the Yankee Dryer after leaving the Thru-Air Dryer.				

* F (Fourcraier), TW (Twin Wire), O (Other)