# PULPING CHARACTERISTICS AND PAPER MAKING POTENTIAL OF NON-WOOD WETLAND PLANTS



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MASGP-80-016

Reference Citation

This report should be cited:

de la Cruz, A.A. and G.R. Lightsey. April 1981. Pulping characteristics and paper making potential of non-wood wetland plants. Mississippi-Alabama Sea Grant Consortium Publication No. MASGP-80-016. Ocean Springs, Mississippi. 66 pp.

This work is a result of research sponsored in part by NOAA Office of Sea Grant, U. S. Department of Commerce under Grant No. NA80AA-D-00017, the Mississippi-Alabama Sea Grant Consortium and the Mississippi State University. The U. S. Government is authorized to produce and distribute reprints for governmental purposes notwithstanding any copyright notation that may appear hereon.

# Pulping Characteristics and Paper Making Potential of Non-wood Wetland Plants

A Technical Report

1980 Sea Grant Project No. R/MT-2

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Published by Mississippi-Alabama Sea Grant Consortium
Caylor Building
Gulf Coast Research Laboratory
Ocean Springs, Mississippi 39564

April 1981

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## Acknowledgments

This work was supported by a grant from the Mississippi-Alabama Sea Grant Consortium. We thank Fe Blanche, James Cutler, David Gains, Virginia Mabesa, and Emma Wilson for assistance in the laboratory work. Samuel Faulkner and Keith Mangrum helped in the collection of plant samples. We are grateful to Vicki Bennett and Lyda Eubank for secretarial assistance.

Dr. Gary D. McGinnis of the Forest Products Laboratory at Mississippi State University participated in the alpha cellulose and alcohol determination.

ABSTRACT

The tightening pulpwood supply situation in the world has lead to an urgent search for alternative or supplementary sources of pulp. One source of raw pulp is non-wood plants. The most abundant and productive non-wood plants are the grasses, particularly those growing in the vast wetlands of the world. The pulping characteristics and paper making potential of selected marsh plants common in the Mississippi Gulf Coast were investigated. The dry stem biomass of *Phragmites communis*, *Spartina cynosuroides* and *Typha latifolia* contained 38, 33, and 30% pulp respectively. The strength properties of paper sheets made from marsh plant pulps are comparable to woody pulp either because of similarities in fiber length (e.g., *Phragmites* - 1.0 to 3.3 mm, *Spartina* - 0.6 to 2.4 mm, *Typha* - 0.4 to 2.2 mm) or due to the good interfiber bonding quality of marsh plant fibers (e.g., the leaves of the other species investigated). Marsh plant pulp can be blended with wood pulp for bulk or to increase paper strength or texture quality. *Spartina cynosuroides* had the highest cellulose content (35%) and *Phragmites* the highest concentration of six-carbon sugars (70%). The feasibility of farming the wetlands for pulp, cellulose, or alcohol exists. However judicious conservation and management measures should be practiced in order to protect the structural integrity and global functions of wetland ecosystems.

# INTRODUCTION

The demand for raw pulp materials increased tremendously during the last decade and is predicted to continue to increase to "shortage" level (Steenborg 1973). The accelerated harvesting of wood products and conversion of forest areas to other land uses have put pressures that threaten the ecology of even the great forests of the world. In countries where there is limited forest fiber supply, the pressure is acute and the search for alternative or supplementary sources of raw materials is of urgent concern.

Pulp from Non-wood Plants. One source of raw pulp that has long been recognized is non-wood plant fiber. Historically, the first "paper" invented by man in ancient time was from a non-wood plant, the swamp sedge *Cyperus papyrus*. Papyrus was the predecessor to parchment and subsequently to true paper. It was invented in Egypt and was the chief medium of literature expression, religious documents and business transactions from the fifth century B.C. to the fourth century A.D. Atchison (1973) in his review of the present status and future potential of non-wood plant fibers, estimated that only 5% of the total fibrous materials utilized for pulp and paper on a world-wide basis comes from non-wood fibers. Since mid-1960's, the world-wide average increase in the use of these fibers has amounted to about 10%, with average annual increases in Latin America, Africa, and Asia-Pacific areas (excluding Japan and Oceania) amounting to about 20%. Because of the tightening pulpwood supply situation and the resultant increased cost of pulpwood in the major producing areas, the utilization of non-wood fibers will undoubtedly increase. In North America, which has an abundance of soft and hardwoods and uses only 1% of non-wood fibers, the search for supplementary sources of pulp has already begun.

For now, non-wood plant fiber is particularly important for the developing countries in the Middle East, Asia, parts of Africa, and Latin America. In some countries, for example Romania, non-wood pulps represent more than 50% of the overall fibers furnished for paper and paperboard.

The various types of non-wood plant fibers can be categorized as follows:

1) Agricultural by-products such as sugarcane (*Saccharum officinarum*) bagasse, corn (*Zea mays*) stalks, sorghum, (*Sorghum bicolor*), rice (*Oryza* sp.), wheat (*Triticum* sp.) and other cereal straws;
2) Non-wood crop fibers which are grown primarily for their fiber content. These include: a) bast fibers of jute, hemp (*Cannabis sativa*), ramie (*Boehmeria nivea*), kenaf (*Hibiscus cannabinus*), sunn hemp (*Crotalaria juncea*), okra (*Hibiscus esculentus*), flax tow (*Linum usitatissimum*), and old rope or rags made from such fibers; b) leaf fibers such as abaca (*Musa textilis*) or manila hemp, sisal (*Agave sisalina*), henequen, banana, and pineapple fiber; c) cotton (*Gossypium* sp.) fiber, cotton linters and cotton rags.
3) Natural growing plants such as algae, seagrasses, bamboo, papyrus, esparto grass (*Stipa tenacessima*) other dryland grasses (e.g., *Imperata cylindrica*), reeds (e.g., *Arundo* and *Phragmites*) and other wetland plants.

Among these non-wood pulps, the use of bagasse from sugarcane as soda pulp has made substantial headway in the paper and pulp industry (Misra 1975). Various paper products have been manufactured from bagasse mixed with wastepaper, kraft pulp, and wood pulp - such as grocery bags, writing and printing paper (Bhat and Virmani 1954), sanitary tissues, and other varieties of light papers. In the Philippines, paper packaging material has been manufactured from 100% bagasse (Zerrudo 1978). Other agricultural residues that have been successfully used in the manufacture of a variety of writing, printing, and packaging paper products are rice straw in Egypt and the Republic of China (Ibraim 1975); wheat, rye, oat, and barley straws in Italy and the Netherlands (Atchison 1973); corn stalks and corncobs which contain 32-34% cellulose have been shown also to produce paper of adequate quality and sufficient strength when mixed with wood pulp (Raymond and Lightsey, Unpublished manuscript). There is extensive research on the use of non-wood crop fibers for products other than paper, e.g., abaca rope, ramie cloth, etc. (Batugal et al., 1978). Although the U.S. Department of Agriculture's Northern Regional Research Laboratory for many years has been screening fiber crops as raw materials for production of pulp and paper, the tempo in the world-wide consideration of non-wood crop fibers for pulping and paper making has been very slow. Two crops that have received considerable attention in recent time is kenaf (*Hibiscus cannabinus*) and sisal (*Agave sisalina*). For several years now, the Research Center of the American Newspaper Publishers Association Research Institute has been working on the utilization of kenaf for newsprint manufacture (Erwin Jaffe, personal communication). Pulping characteristics (Touzinsky et al. 1973), field production methods (Bagby et al. 1975), and economic potential (Moore et al. 1975) of kenaf have been investigated. Sisal as a source of high grade paper has received much attention from the Mexican government. A Sisal Development Program is in operation since 1977 in the Yucatan. The Mexicans are in the process of developing more efficient sisal farming methods and land management schemes to achieve the goal of producing 100,000 tons of sisal pulp annually. It takes 18 tons of raw green leaf to produce one ton of high grade sisal pulp (Anonymous 1981).

Another source of pulp that has gained increasing recognition in the last decade are the naturally growing plants in marine bays, mountain prairies, coastal swamplands and other types of "wastelands." Isolated uses of algae in paper making has been reported in the literature as far back as the 18th century and in 1963 a report of a Russian mill that harvested Cladophora from nature and then made it into different forms of paper appeared in the literature (Nieboer 1965a; 1965b). Leopold and Marton (1975) found Cladophora bleached pulp to be usable as an additive to pulp stocks of lower grades of paper such as newsprint and unbleached pulp used to make corrugating medium and fiber and particle boards. Nieboer (1964) in reviewing the pulping of algae for paper making mentioned other species of algae that have been investigated, namely Sargasso seaweed (Sargassum baciferum and S. vulgare), water wool (Tribonema and Conferva), and giant kelp (Laminaria spp.). The seagrass Zostera (Leopold and Marton 1975) and the sea plant Posidonia australis (Nieboer 1964) have also been pulped. While Posidonia did not show any promise either as paper or textile fiber due primarily to high production costs, the pulp from the seagrass _Zostera_ can be used as additive to newsprint or corrugating medium. Meanwhile, the pulping characteristics of the aquatic weed pest _Eichornia_ spp., the common water hyacinth, has received both high (Zerrudo et al. 1978) and low ratings (Anonymous 1976; Monsod 1979).

Literature is available about pulp and paper production from bamboo in Brazil and a number of Asian nations; from esparto grass in France, Spain, Algeria, and Tunisia; and from sabai grass in India and Pakistan (Atchison 1973). The cogon grass _Imperata cylindrica_ is one of the most widely distributed grasses, especially in open country and abandoned or deforested areas where it may be the chief ground cover. It can be found in a variety of environments since it tolerates a wide range of soil conditions from sub-arid to swampy, and is found from sea level to 200 m altitude. It is the most common grass in tropical Africa to the Mediterranean and Southern Europe, and east to India, China, Japan and Malay Archipelago, and Australia. Experiments conducted by Richmond (1906) as well as numerous experiments conducted by the Philippine government have shown that cogon (Sorrosa et al. 1972) and the talahib grass _Saccharum spontaneum_ can be made into good paper. Richmond (1906) found that cogon pulp readily bleaches to a clean white color.

_Farming the Wetlands for Pulp_. In recent years, studies on wetlands, particularly tidal swamps and coastal marshes, revealed among other things, the high primary production capacity of this type of ecosystem (Odum 1973; Whittaker 1975). In general, the dominant vascular vegetations of temperate marshes and swamps are grasses (e.g., _Spartina_ spp.), sedges (e.g., Scirpus spp.), and rushes (e.g., Juncus spp.) which follow a life cycle of mid-winter death, accelerated spring growth, summer bloom, and autumn senescence. By winter marsh grasses like the spartinas and phragmites have lost their leaves and only the dead stalks remain standing on the marsh. Eventually all the dead materials fall on the marsh floor and get incorporated in the aquatic medium.

There has been a long history of use of wetland vegetation products (de la Cruz 1976) as sources of housing and clothing materials, and as sources of fuel, medicine and food. The potential value of marsh grasses and swamp reeds in pulping industry has been reported for the cattail weed Typha spp. and the papyrus reeds Cyperus papyrus (Anonymous 1976). The most impressive use of a wetland plant is the Romanian government's program to produce pulp and other cellulose derivatives from the common swamp reed Phragmites communis (de la Cruz 1978). More than 60% of the 4,000 $km^2$ delta of the Danube River is covered with Phragmites with an average annual growth of about 3,000,000 metric tons. In 1956, the government began to farm and use it, and now the reed beds are carefully managed and their productivity improved. The reeds are harvested, stored, and transported with machinery and techniques designed specially for the marsh terrain by the Danube Delta Institute at Tulcea. Harvested reeds are converted to pulp in a pulp mill at Braila, a short distance inland from Tulcea. Printing paper, cellophane, cardboard, and various synthetic fibers are derived from this pulp. The raw reeds and pulpmill wastes yield a variety of other products, notably cemented reed blocks and compressed fiber board; furfural and alcohol; insulation material; fuel sticks and briquettes; and fertilizer. With an annual harvest of about 125,000 tons, farming of the Danube Delta reeds has become vital to the Romanian economy.

Reed pulp production also occurs in the USSR and in the People's Republic of China with a combined annual yield of 145,000 metric tons. A small reed pulp mill is operating in Egypt's Nile Delta, and one in Iraq where about 1,000,000 tons of reeds are grown annually in the delta of the Tigris and Euphrates Rivers. Vast quantities of reed material is available, and with the intensive pulping and paper-making program utilizing this raw material being underway in Romania and Soviet Union, it is expected that its use will increase in these areas.

Coastal wetland ecosystems have the advantage of a fairly stable natural fertility coupled with relatively free energy subsidies in the forms of tidal inundations, dissolved nutrients, and detrital substances coming from inflowing streams and rivers. The Romanian system of reed farming for instance, is based on the reeds' natural production cycle. The reeds are harvested in winter after they have shed most of their leaves. Then without further attention (e.g., plowing,fertilization, or chemical treatment) they are left to grow back naturally from their underground rhizomes during spring and summer.

Studies recently conducted on certain management tools such as burning (de la Cruz and Hackney 1980), harvesting (Stout et al. 1978), and fertilization (de la Cruz et al. 1980) indicated that these cultural alterations can be used to stimulate the productivity and increase the biomass yield of wetland plants.

Harvesting the marsh periodically may be beneficial because it opens up the marsh floor to sunlight and allows freer flow of tidal waters leading to enhancement of productivity. De la Cruz and Hackney (1980) reported that a Spartina marshland can be harvested annually and a Juncus wetland every three years without damage to the system. If this is the case, harvesting the marsh periodically will be beneficial, not only in the enhancement of marsh productivity, but also as a regular source of raw material for fiber. Pulping is a suitable enterprise because of its economic potential in countries with limited forest resources but with extensive swamplands. Further, marsh vegetations are fast growers and can be reharvested between 1-3 years and the foliage is left on the marsh during harvest to undergo its natural decay and incorporation in the natural aquatic food webs and nutrient cycles.

Objectives. The objective of this investigation is three-fold: (1) to determine the amount of recoverable crude pulp from selected species of marsh plants growing in the Mississippi Gulf Coast and to measure the dimension of pulp fiber; (2) to evaluate the tear, burst, folding, and tensile strength of the paper made from marsh plant pulps; and (3) to compare the strength quality of paper made from pulp mixtures of marsh plant species and when marsh pulps are combined with wood pulps or recycled paper kraft.

## MATERIALS AND METHODS

### Collection and Preparation of Plant Materials.

The species of vascular plants commonly found on the coastal marshes of Mississippi considered in this study were: the common sawgrass *Cladium jamaicense* Crantz (Cyperaceae); black needlerush *Juncus* roemerianus Scheele (Juncaceae); common reed Phragmites communis Trinius (Gramineae); sedge bulrush Scirpus olneyi Vahl. (Cyperacea); smooth cordgrass Spartina alterniflora Loisel (Gramineae); giant cordgrass Spartina cynosuroides (L.) Roth. (Gramineae); and the broadleaf cattail Typha latifolia L. (Typhaceae).

Only the aboveground portions (culm) of the plants were harvested by clipping the base a few centimeters above the ground surface. Phragmites and Spartina spp. have emergent stems while the rest of the other species have underground stems (or rhizomes) and their aboveground portions are mainly leafy materials. The plant materials (except S. alterniflora) were collected from different parts of the Mississippi Gulf Coast where the species grew in abundant monospecific stands during late winter when the plants were dead. Samples of S. alterniflora were obtained from a marsh near Moorehead City, North Carolina. The plants were transported to the laboratory and processed as follows: (1) leaves and stems were separated in Phragmites and Spartina spp.; (2) the leaves were cut with scissors and the stems were chopped with a garden shear into 1 cm chips; (3) stem chips of Phragmites and Spartina spp. and their leaf fragments as well as those of Cladium, Juncus, Scirpus, and Typha were analyzed for pulp after drying to constant weight at 85°C.

Pulping Procedures.

Crude pulp was extracted in a bench mounted, Parr Pressure Reaction Apparatus Model 450 (Figure 1) with a 2000 ml bomb assembly and manual temperature controller mounted on a Variac transformer case with a pulping liquid consisting of sodium hydroxide and sodium sulfite (Kraft solution). Extraction efficiency was tested using 50 and 100 g

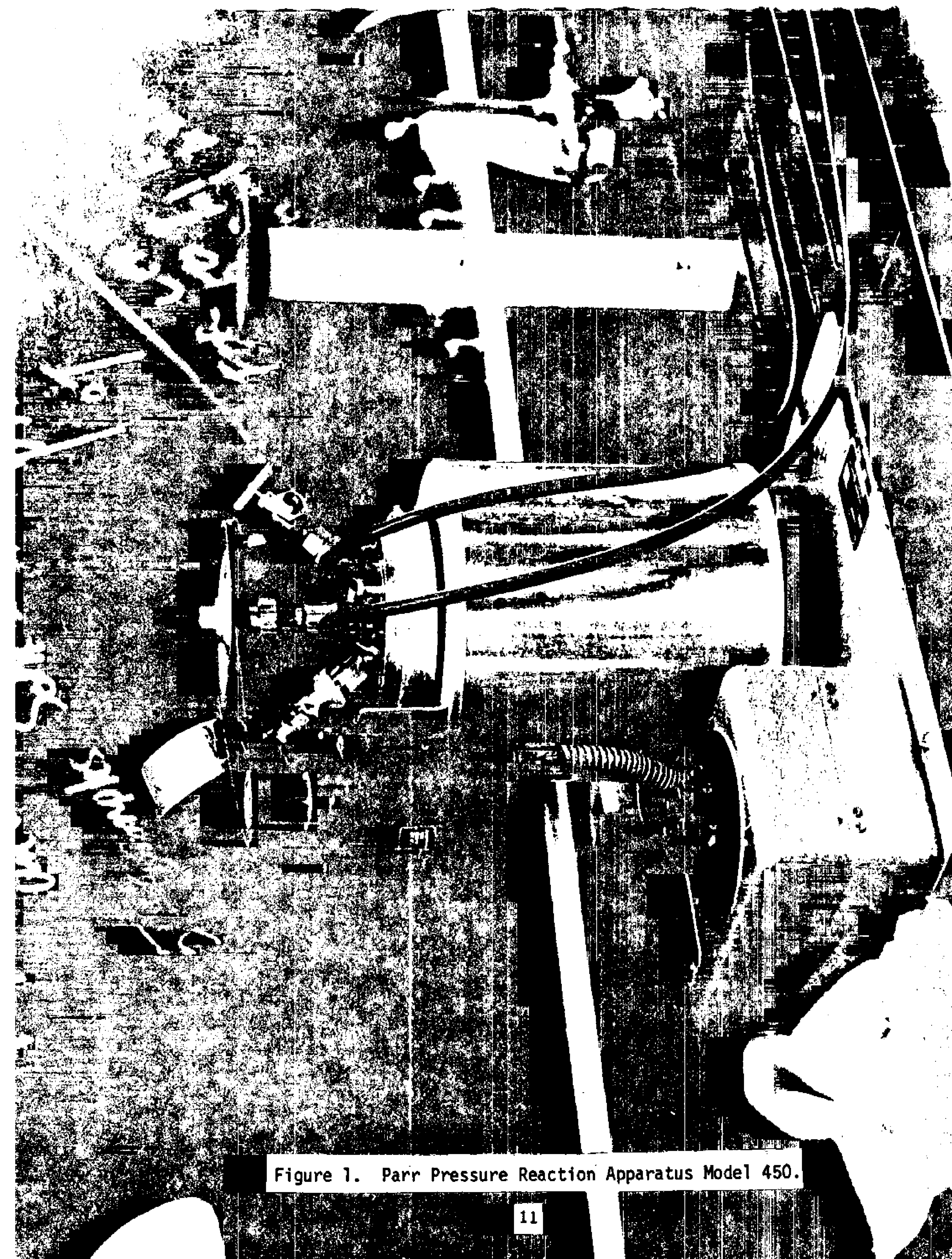

Figure 1. Parr Pressure Reaction Apparatus Model 450.

plant samples in 1000 ml Kraft solution of two concentrations: solution I - 50 g NaOH and 10 g $Na_2S$ and solution II - 30 g NaOH and 10 g $Na_2S$ per liter of distilled water. All extractions were then conducted using 50-75 g leaf material or 75-100 g stems using Kraft Solution II according to the following protocol:

1) The plant material was placed in the reactor chamber. One liter of pulping liquid (Kraft solution II) was added. The chamber assembly was carefully sealed and inserted into the heating unit.
2) The chamber was heated slowly to 170°C by setting the manual temperature controller to 100 and manipulating the pressure valve control to adjust the pressure to 100-120 psi. When the desired temperature was attained, the temperature controller was set back to 60 which held the temperature at 170°C and the pressure at 100 psi.
3) After 1 hr, the reactor was switched off, tap water was run through the cooling coil inside the chamber while the reactor chamber is being removed from the heating unit. The chamber was dipped in the sink containing cold water. Cooling was achieved within 10 to 15 minutes.
4) The pressure valve of the reactor was then released and the clamps holding the chamber lid were disengaged by loosening the bolts. The chamber was opened and the plant material (pulp and shives) were cautiously transferred into an enameled pan.
5) The pulp was washed thoroughly in running water through a fine sieve. The fiber bundles were broken up by agitation in a

blender at slow speed. The pulp was re-sieved and the shives (unpulped splinters, fragments or husks) were picked from the bulk with a tweezer.

6) The shives were concentrated in an aluminum cup, dried to constant weight at 85°C and weighed.

7) A small sample was resuspended in water in a glass vial and put aside for microscopic analysis.

8) The pulp was hand squeezed, placed in a plastic bag, sealed, refrigerated for at least 24 hr, and then weighed.

9) Another small subsample was taken, placed in a weighing cup, weighed, then dried to constant weight at 85°C. The dry to wet weight ratio was calculated and the water loss factor was applied in estimating the dry weight of the total pulp mass.

10) The pulp yield was determined as follows:

a) $\text{Percent pulp} = \frac{\text{weight of pulp and shives (total wt)}}{\text{weight of plant material}}$

b) $\text{Percent shives} = \frac{\text{weight of shives}}{\text{total weight}}$

11) The pulp was stored in airtight sealed plastic bags under refrigeration.

Microscopic Examination of Fiber.

A small sample of the wet pulp was spread on a glass slide with dissecting needles in a drop of water. The preparation was covered with a glass slip and examined in a compound microscope under low power (x 30.5) magnification. A Whipple micrometer disc provided with a 7.5 mm square divided into 100 parts, with one square subdivided into 25 parts was used in the measurement of fiber dimensions. Five measurements were taken of each sample replicate under high power magnification (x 305). The data were then pooled for each pulp or plant species and a statistical mean computed for the length and width of pulp fiber.

Determination of Alpha Cellulose.

Alpha cellulose in pulp was determined at the Mississippi State University Forest Product Laboratory according to standard procedure routinely used in the laboratory. Ovendried samples of crude pulp was macerated in increasing volume of 5 M (17.5%) sodium hydroxide for a total contact time of 40 minutes with reagent. The cellulose was filtered-washed in 8.7% NaOH solution, distilled water, and soaked in 10% acetic acid. The material was air dried after rinsing the acid with distilled water. The alpha-cellulose content of the plants was estimated in terms of percentage in crude pulp and percentage in raw plant material.

Pine Pulp and Recycled Paper Kraft.

Kraft pulp from loblolly pine and recycled paper were used for comparative purposes, and to blend with marsh pulp. The pine kraft pulp was obtained from the St. Regis Paper Company of Monticello, Mississippi. Recycled kraft was obtained by soaking fragmented pieces of used grocery paper sacs in water for 3 days. The wet fragments were then broken down into individual fibers in a blender. Both pine pulp and recycled kraft were hand squeezed, stored, and treated in the same manner as the marsh plant pulp.

Making Paper Sheets.

A Williams Standard Sheet Mould with a 8 x 8 inches deckle plate was used in making the paper sheets. Seventy-five grams (wet weight) of pulp was resuspended in water, agitated for 2 minutes in a slow speed blender, and then poured into the sheet mould. After the paper sheet was formed, the deckle holding the wet sheet was pressed manually with a metal roller to remove excess water. The pressed sheet was then transferred onto a fine screen and dried in a forced air oven overnight at 85°C under a 2 kg weight (bricks). The dried paper sheet was then trimmed of its edges and cut with a small desk type paper cutter into the required sizes needed for the various strength tests as follows: 15 mm (5/8 inch) wide strips for the fold test; 51 x 51 mm (2 x 2 inches) squares for the burst test; 76 x 63 mm (2 1/2 x 3 inches) rectangles for the tear test; and 12 mm (1/2 inch) wide strips with a dog-bone shape for the tensile test.

All of the paper sheets made from both pure crude marsh plant pulp or mixtures of pulps were prepared, moulded, pressed, and dried as uniformly as possible; and they were all handled and stored under uniform conditions. A total of 39 kinds of paper sheets in triplicates were made. Table 1 is a list of the various paper sheets made from marsh plant pulps, kraft pulp from loblolly pine, recycled paper, and combinations of these materials.

Paper Strength Test.

Each of the paper sheets listed in Table 1 was tested for tearing, bursting, folding and tensile strengths using appropriate instruments. The different paper testers (Figure 2 to 5) are designed to measure specific properties of paper. One important factor in the measurement of paper is the thickness of the specimen. Each strip or square of paper tested was measured for thickness with a vernier caliper with

Table 1. List of paper sheets tested: Kind, amount of pulp, and sample combination.

| Code No. | Kind and Blend | Wet Weight & Ratio |
|---|---|---|
| 01 | Recycled paper | 75 g |
| 02 | Loblolly pine | 75 g |
| 03 | Recycled paper and pine pulp | 37.5:37.5 g |
| 04 | *Typha* leaves | 75 g |
| 05 | *Typha* stem and recycled paper | 25:50 g |
| 06 | *Typha* stem and *Phragmites* stem | 37.5:37.5 g |
| 07 | *Typha* stem | 75 g |
| 08 | *Typha* stem and pine | 25:50 g |
| 09 | *Spartina alterniflora* leaves | 75 g |
| 10 | *Spartina alterniflora* leaves and recycled paper | 25:50 g |
| 11 | *Spartina alterniflora* stem and *Phragmites* stem | 37.5:37.5 g |
| 12 | *Spartina alterniflora* stem | 75 g |
| 13 | *Spartina alterniflora* stem and pine | 25:50 g |
| 14 | *Spartina cynosuroides* leaves | 75 g |
| 15 | *Spartina cynosuroides* stem and recycled paper | 25:50 g |
| 16 | *Spartina cynosuroides* stem and *Phragmites* | 37.5:37.5 g |
| 17 | *Spartina cynosuroides* stem | 75 g |
| 18 | *Spartina cynosuroides* stem and pine | 25:50 g |
| 19 | *Phragmites* leaves | 75 g |
| 20 | *Phragmites* stem and recycled paper | 25:50 g |
| 21 | *Phragmites* stem | 75 g |
| 22 | *Phragmites* stem and pine | 25:50 g |

Table 1. (Continued)

| Code No. | Kind and Blend | Wet Weight & Ratio |
|---|---|---|
| 23 | *Juncus* | 75 g |
| 24 | *Juncus* and recycled paper | 25:50 g |
| 25 | *Juncus* and *Phragmites* | 37.5:37.5 g |
| 26 | *Juncus* and pine | 25:50 g |
| 27 | *Scirpus* | 75 g |
| 28 | *Scirpus* and recycled paper | 25:50 g |
| 29 | *Scirpus* and *Phragmites* | 37.5:37.5 g |
| 30 | *Scirpus* and pine | 25:50 g |
| 31 | *Typha* leaves and pine | 25:50 g |
| 32 | *Spartina alterniflora* leaves and pine | 25:50 g |
| 33 | *Spartina cynosuroides* leaves and pine | 25:50 g |
| 34 | *Phragmites* leaves and pine | 25:50 g |
| 35 | *Cladium* leaves and pine | 25:50 g |
| 36 | *Cladium* stem | 100 g |
| 37 | *Cladium* and *Typha* | 50:50 g |
| 38 | *Cladium* and recycled paper | 30:70 g |
| 39 | *Cladium* and pine | 30:70 g |

a fine adjustment and calibrated in 0.001 inch increments. Three measurements were taken of each specimen and the average thickness in mils (thousandth of an inch) was converted to centimeters (thickness in mils x 2.54 x $10^{-3}$).

Elmendorf Tearing Tester (Model 60-100). This is the standard instrument for determining the tearing strength of paper, rubber, pulp, celluloid, cloth tape, etc. As can be seen in Figure 2, the instrument has a sector pendulum which is mounted on ball bearings. This sector carries a clamp and has a dial graduated from 0-100. On the same axis is mounted a pointer which has a constant friction, just sufficient to stop at the highest point reached by the swing of the sector. The paper strip measuring 76 x 63 mm (3 x 2 1/2 inches) is initially cut a certain distance by a fixed cutter and then the weighted sector swings down and tears the sample the remaining distance when the trip mechanism is released. The length of the pendulum swing is determined by the toughness or tear resistance of the material. The maximum length of swing of the pendulum is noted by a pointer. Operation of Tear Tester was done according to TAPPI procedures Manual No. T414 ts-65. The scale reading was recorded to nearest half division and the average force in gram required to tear a single ply was calculated as follows:

Average Tearing Force = Average scale reading x 16 (gm)

The tearing force is expressed as grams force required to tear a single ply of paper a given distance. The work done in tearing is measured by the loss in potential energy of the pendulum on the Tear Tester. With this technique, tearing strength is defined as the average force in grams, required to continue tearing a sheet of paper once a tear has

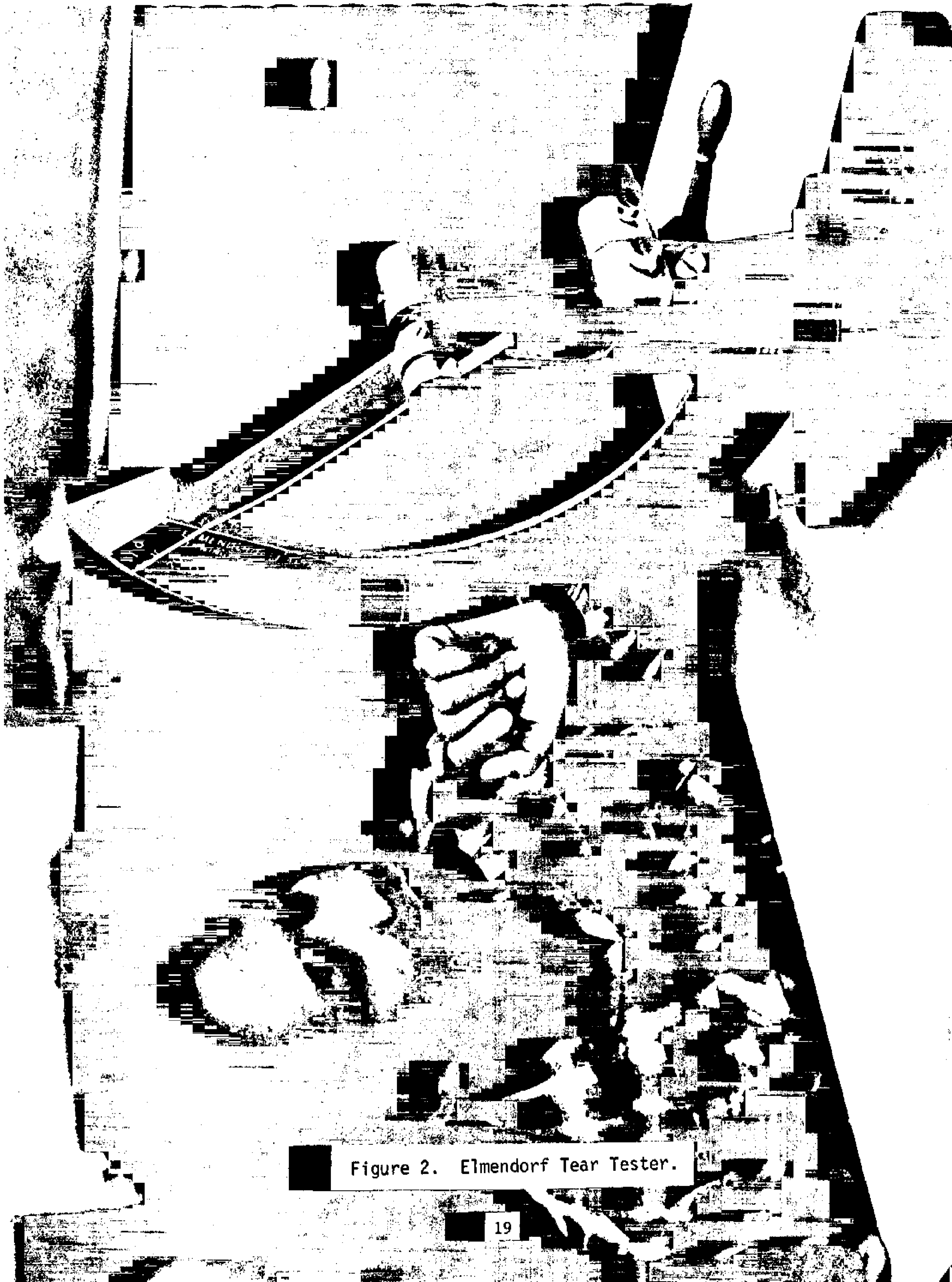

Figure 2. Elmendorf Tear Tester.

been initiated.

Mullen Burst Tester (Model L.C.). This is a hand driven instrument for determining the bursting strength of paper. The Mullen Tester operates on the hydraulic principle and indicates actual bursting strength irrespective of any other factor. A paper test specimen, 51 x 51 mm square, is clamped on top of the hydraulic cylinder which contains glycerine. A rubber diaphragm seals the cylinder. As pressure is applied, the glycerine rises up the cylinder, expanding the rubber seal which impinges on exactly one square inch of the paper sample. The pressure eventually bursts the paper and at that point the pressure gauge indicates the bursting strength in pounds per square inch. Figure 3 is a photograph of this instrument. In this context, the bursting strength of the paper specimen can be defined as the hydrostatic pressure in pounds per square inch required to rupture the paper when pressure is applied at a controlled rate through a rubber diaphragm. The primary function of the bursting test is to indicate the resistance of a paper product to bursting rupture. The procedures used in the operation of the instrument and calculation of burst strength was according to TAPPI Manual No. T403 os-76.

Bursting strength can also be expressed in kilopascals or kilonewtons (kN) per square meter (equivalent to pounds per square inch or psi). The bursting strength of paper is defined as the average force applied over a unit area of paper surface.

Tinus Olsen MIT Folding Endurance Tester (Model 1). This instrument is designed to determine the folding endurance quality of paper and other sheet materials. The paper specimen measuring 10 mm long x

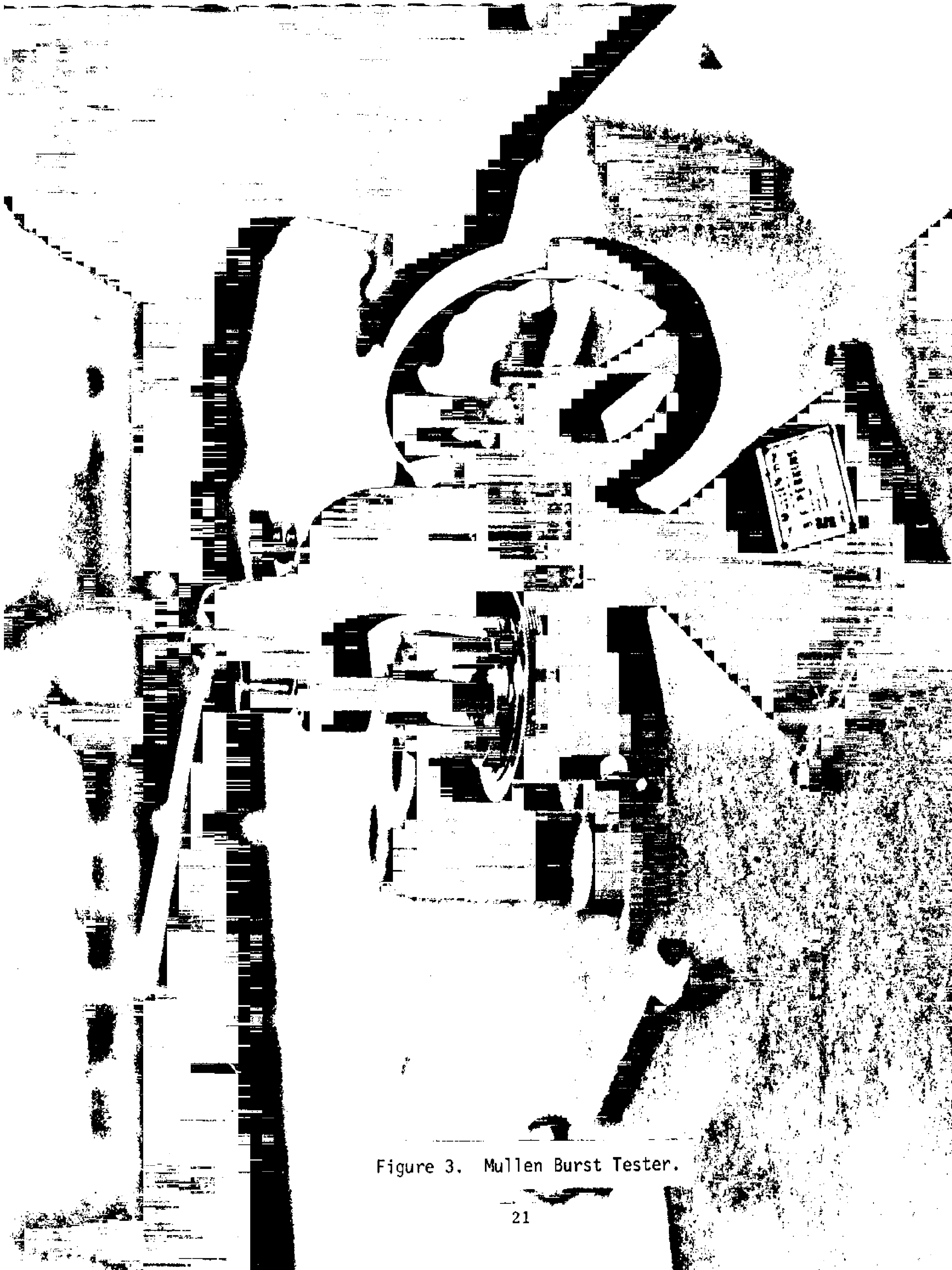

Figure 3. Mullen Burst Tester.

15 mm wide (5 x 0.5 inches) is inserted in the machine (Figure 4). The ends of the specimen are held firmly in the weighing and oscillating heads. A load of 0.5 kg was applied in all the tests conducted. The lower jaw of the machine clamping the lower end of the paper strip oscillates at a speed of 175 double folds per minute. A counter records the number of folds required to sever the specimen. Upon failure, the counter is instantly disconnected and the machine stops. The precise use of the machine and calculation of folding endurance were based on TAPPI procedure described in Manual No. T511 su-69. The number of folds recorded by the machine indicates the resistance of paper to repeated stress. This is directly expressed as number of folds at a particular load, in this case 0.5 kg. In this context, fold endurance is the rate of tensile strength reduction by repeated creasing from its original value to a lower value applied by the instrument.

Dillon Tensile Tester (Model LW). This instrument measures the tensile strength of paper. The test procedure used is described in TAPPI Standard Manual No. T404 os-76. The specimen consisting of paper strips 140 mm long x 12 mm wide (5.5 x 0.5 inches) cut into a dog-bone shape, is clamped into the instrument (Figure 5). Load or force is manually applied by means of a manual gear drive. As the force is applied, a needle gauge records the load on the dynamometer gauge. The tensile force is expressed as kilonewtons per square meter from the following formula:

$$\text{Tensile Strength} = \frac{\text{scale reading (lbs)} \times 0.454\ \text{(kg)}}{\text{thickness (cm)} \times \text{width (m)}} \times 9.8$$

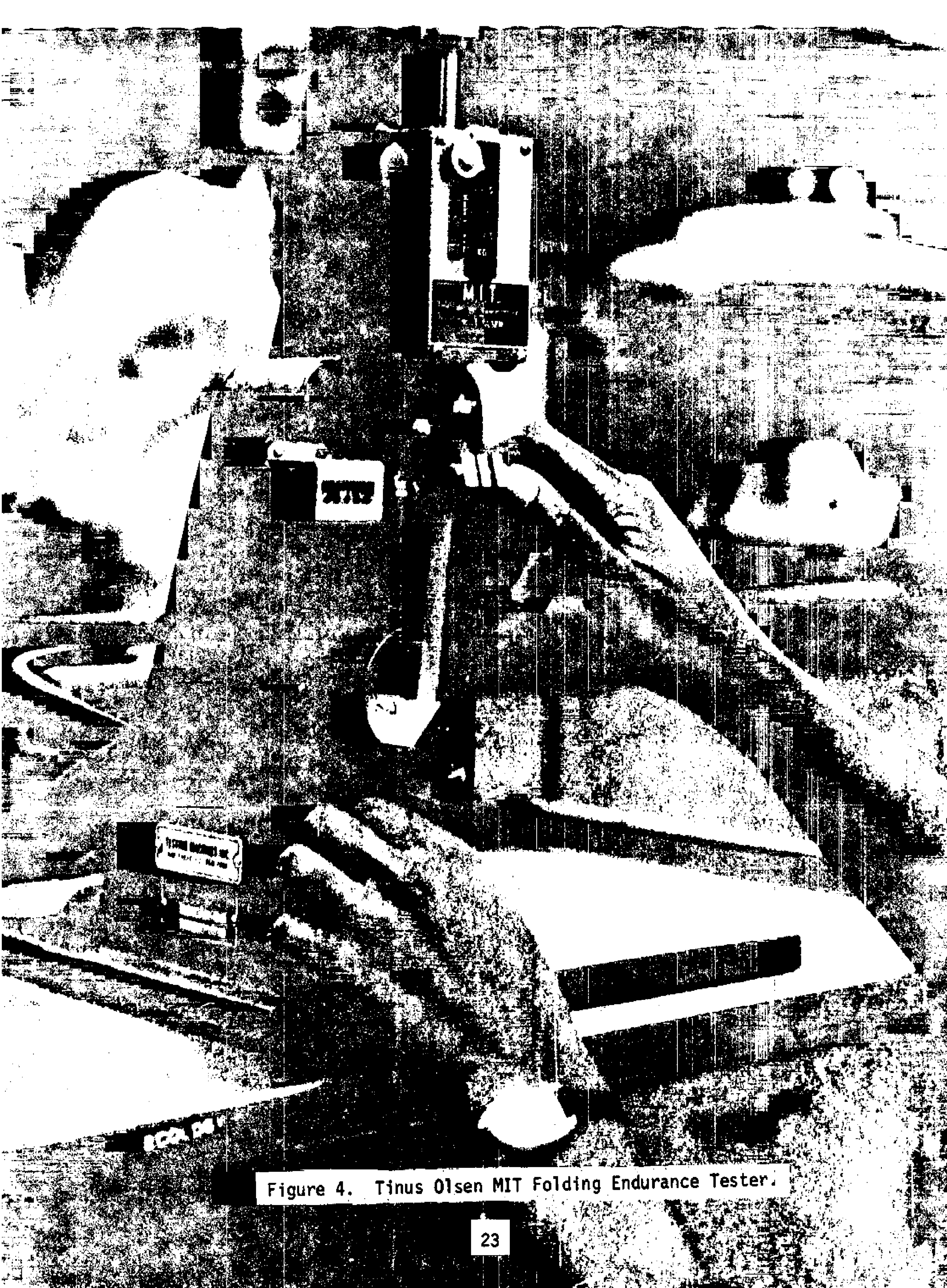


Figure 4. Tinus Olsen MIT Folding Endurance Tester.

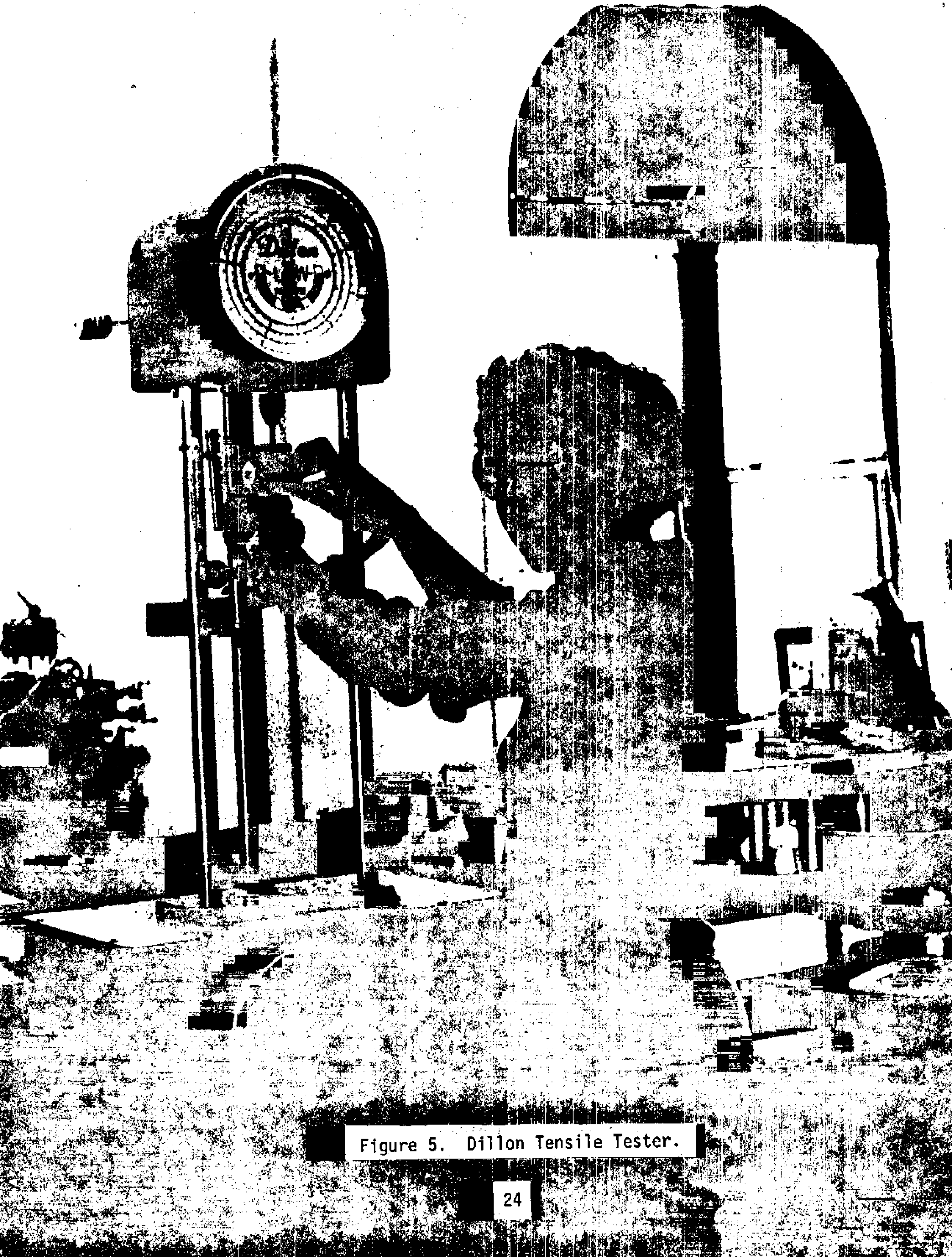

Figure 5. Dillon Tensile Tester.

The tensile strength is defined as the maximum force required to break a specimen in tension per unit cross-sectional area.

## RESULTS

### Pulping Technique

The dissolving action of Kraft solutions I (50 g NaOH:10 g $Na_2S$: 1000 ml $H_2O$) and II (30 g NaOH:10g $Na_2S$:1000 ml $H_2O$) which were tested in the extraction of pulp differed very slightly. The difference summarized in Table 2 was considered insignificant because the percentage of shives remaining after pulping was below 1% in both concentrations. Shives are the bits and pieces of plant materials that remained unpulped after the extraction process. Based on this observation, Kraft solution II was used in all subsequent extractions. Seventy-five to 100 g of the plant materials was generally extracted with 1000 ml pulping solution except for the leaves of *Phragmites*, *Spartina* spp. and *Typha*. Leafy tissues are fluffy and only half of the amount (37.5 to 50 g) would fit the 2000 ml capacity reaction chamber which were extracted with 500 ml Kraft solution II diluted with 500 ml distilled water. A pulping solution of lower concentration would probably delignify the plant material sufficiently but this was not pursued after test-runs using Kraft solution II diluted 100% (i.e., 15 g NaOH:5 g $Na_2S$:1000 ml $H_2O$) yielded incomplete delignification or "half cooked" pulping at the usual cooking conditions of 170°C at 100-120 psi for 1 hr.

### Pulp Content.

The percentage of pulp in the seven marsh plants studied ranged from 14 to 38% based on dry weight and excluding shives. The twelve samples listed in Table 3 can be arbitrarily categorized as follows: (a) low pulp content - 14 to 17%; (b) medium pulp content - 20 to 26%;

and (c) high pulp content - 30 to 38%. As expected, these values are lower than the 40-45% pulp found in hardwoods and the 50-55% pulp content of softwoods in general (Britt 1970). However, the pulp content of some of these non-wood plants are high enough to use as supplementary sources of short fiber raw material. Misra (1971) reported that sugarcane bagasse and wheat straw contains 50-52% and 46-48% crude pulp respectively. A species of bamboo (Bambusa arundinacea) from India yielded 58-60% of bleached pulp (Jauhare et al. 1971). Samples of papyrus (Cyperus papyrus) from Africa which we pulped using our pulping procedure yielded 18% crude pulp. This value is comparable to the 16% of Scirpus, a plant belonging to the same family as papyrus. Phragmites stem has high enough pulp yield (38%) to be considered as a primary source of pulp while the spartinas, cattail and sawgrass stems may be useful as pulp mixtures to increase bulk and as blending pulp to control the quality of paper products. Leaves are usually considered of no value for paper making and they contain a high percentage of silica (Wiederman 1971). Nevertheless, fibers from leaves appeared to have a good bonding quality. As we will discuss later on, the bonding property of fiber is important in evaluating the strength of paper. A farming situation where the leaves are allowed to shed and fall to the ground to undergo natural decay and replenish the nutrients of the soil and the detritus load of the water is ecologically sound for cultural management of wetlands.

Alpha Cellulose Content and Potential for Alcohol Production

The values obtained for alpha cellulose when samples of crude pulp were subjected further to sodium hydroxide treatment at maximum

Table 2. Percentages of pulp and shives recovered from 100 g plant material after extraction with Kraft Solution I (50 g NaOH: 10 g $Na_2S$:1000 ml $H_2O$) and II (30 g NaOH:10 g $Na_2S$:1000 ml $H_2O$).

| | Kraft Solution I | | Kraft Solution II | |
|---|---|---|---|---|
| | % Pulp | % Shive | % Pulp | % Shive |
| *Phragmites communis* stem | 35.74 | 0.20 | 40.69 | 0.22 |
| | 35.29 | 0.06 | 40.96 | 0.22 |
| | 36.41 | 0.17 | 40.29 | 0.38 |
| | 36.97 | 0.14 | 34.98 | 0.63 |
| | 38.15 | 0.19 | 40.14 | 1.17* |
| *Spartina cynosuroides* stem | 28.27 | 0.0 | 39.62 | 0.05 |
| | 29.96 | 0.0 | 29.11 | 0.18 |
| | 33.24 | 0.02 | 33.37 | 0.75 |
| | 31.66 | 0.05 | 36.95 | 2.02* |
| | 31.86 | 0.11 | 29.50 | 0.15 |
| | -** | - | 35.57 | 0.11 |
| *Spartina alterniflora* stem | 23.50 | 0.0 | 26.80 | 0.0 |
| | 20.95 | 0.0 | 22.86 | 0.0 |
| | 20.89 | 0.0 | 25.87 | 0.0 |
| | 25.52 | 0.0 | 30.33 | 0.0 |
| | 19.32 | 0.0 | 25.70 | 0.11 |
| *Juncus roemerianus* culms | 13.87 | 0.01 | 17.47 | 0.29 |
| | 11.75 | 0.0 | 15.67 | 0.19 |
| | 12.46 | 0.03 | 13.41 | 0.02 |
| | -** | - | 13.63 | 0.31 |
| | - | - | 13.84 | 0.08 |
| | - | - | 15.67 | 0.32 |

* These are the only extractions using Kraft Solution II that yielded more than 1% shive.

** These four runs were incomplete due to leak in the reactor chamber.

Table 3. Percentage of pulp recovered from selected non-wood wetland plants.

| Plant/Species | Plant Part | No. Sample | Per Cent Pulp Mean | S.D. |
|---|---|---|---|---|
| *Phragmites communis* (Common Reed) | Stem | 10 | 37.96 | 2.40 |
| | Leaves | 5 | 19.98 | 3.62 |
| *Spartina cynosuroides* (Giant Cordgrass) | Stem | 16 | 32.66 | 2.95 |
| | Leaves | 5 | 21.98 | 3.54 |
| *Spartina alterniflora* (Smooth Cordgrass) | Stem | 10 | 24.19 | 3.29 |
| | Leaves | 3 | 21.50 | 2.23 |
| *Typha latifolia* (Broadleaf Cattail) | Stem | 12 | 29.84 | 2.63 |
| | Leaves | 4 | 27.67 | 1.55 |
| *Cladium jamaicenses* (Sawgrass) | Stem | 10 | 26.52 | 1.91 |
| | Leaves | 4 | 16.42 | 1.74 |
| *Juncus roemerianus* (Black Needlerush) | Culm | 9 | 14.21 | 1.78 |
| *Scirpus olneyi* (Bulrush) | Culm | 14 | 16.31 | 1.83 |

dissolving power were very high indicating that both lignin and the hemicelluloses were removed during normal pulping. As can be seen from Table 4, the percent alpha cellulose in crude pulp ranged from 75 to 107% (based on plant biomass). These values multiplied by the percentage of crude pulp in the plant material are equal to the total percentage of alpha cellulose in the plant biomass. Stems of Phragmites, Spartina cynosuroides, Typha and Spartina alterniflora showed cellulose values of 29, 35, 28, and 25% respectively which are somewhat lower than those found in wheat straw (68-69%) and bagasse (75-77%) (Misra 1971). Gas chromatographic analysis of four of the samples analyzed for alpha cellulose (i.e., Spartina cynosuroides, Spartina alterniflora, Cladium stems; and Phragmites leaves) showed that the only sugar present was D-glucose from cellulose.

Preliminary investigations conducted at the Mississippi State University Forest Products Laboratory on Phragmites communis also indicated that about 70% of Phragmites dry biomass can be fermented to alcohol. Six-carbon sugars are the type of carbohydrate which is convertible to alcohol. This observation suggests that the soluble compounds in Phragmites after pulp fibers have been removed, are primarily 6-carbon sugars thus a very high alcohol production potential.

Fiber Dimension

The principal cellular constituent of the seven non-wood wetland plants studied were the slender fibers which are generally pointed at both ends. Other plant tissues seen on the slide preparation of teased pulp include: (a) partially separated epidermal cells which were more abundant in the leaves than in stem pulp; (b) vessel elements

Table 4. Tabulated summary of crude pulp and alpha cellulose yield of marsh plants.

| Plants/Parts | Per Cent Pulp | Estimated Per Cent of Cellulose in Crude Pulp | Per Cent Cellulose in Plant Material |
|---|---|---|---|
| Phragmites communis (stem) | 38 | 75 | 29 |
| Spartina cynosuroides (stem) | 33 | 107* | 35 |
| Typha latifolia (stem) | 30 | 90 | 28 |
| Spartina alterniflora (stem) | 24 | 105* | 25 |
| Cladium jamaicense (stem) | 27 | 88 | 20 |
| Phragmites communis (leaves) | 20 | 75 | 21 |
| Spartina cynosuroides (leaves) | 22 | 93 | 20 |
| Spartina alterniflora (leaves) | 22 | 103* | 23 |
| Juncus roemerianus (culm) | 14 | 93 | 13 |
| Scirpus olneyi (culm) | 16 | 84 | 14 |

*Based on total plant material

which were easily recognizable because they are large and with blunt ends; and (c) fragments of undissociated parenchyma cells.

The dimensions of the fibers ranged from 0.4 to 3.3 mm in length with mean values of about 0.75 to 1.7 mm, and 0.5 to 14.3 μm in diameter with mean values of 0.75 to 6.75 μm (Table 5). Of the seven plants studied, Phragmites has the longest fibers (1.0 to 3.3 mm) with a mean diameter of 6.75 μm. This is comparable to the 1.5 to 3.0 mm fiber length reported by TAPPI (1978) for this reed. Fibers of wetland plants studied were generally short (1.0 - 1.5 mm) compared to woody plants (1.0 - 5.0 mm), however, some non-wood pulp can have rather long fibers (e.g., ramie - 120 mm; hemp - 20 mm; cotton stalk - 10 to 25 mm). Other non-wood plants (Table 6) have short fibers but with fiber diameter bigger than the wetland plants we investigated.

Ash and Caloric Contents.

All the wetland plants examined had less than 10% ash and caloric values of 4.3 to 4.5 kilocalories per gram (Table 7). That at least 90% of the plant biomass is combustible carbon indicates further the high amount of extractable carbon compounds (e.g., sugars) in these plants. As an energy source, the seven species analyzed all contain about the normal range of calories per gram of plant tissue. The potential of some of these plants (e.g., Phragmites and Spartina) as sources of fuel, either in the form of fuel wood, compressed briquettes, or alcohol exist. In countries with scarce forest resources and short supply of fuel-energy, wetland vegetations, if they exist in great quantities, can be an alternative or supplementary source of not only pulp, but energy and chemical derivatives.

Table 5. Summary of fiber measurements

| Plant Species | | No. Fibers Measured | Fiber Length (mm) Range | Mean | S.D. | Fiber Diameter (μm) Range | Mean | S.D. |
|---|---|---|---|---|---|---|---|---|
| *Phragmites communis* (Common Reed) | Stem | 250 | 1.0 - 3.3 | 1.65 | 0.52 | 2.3 - 14.3 | 6.75 | 0.60 |
| | Leaves | 25 | 1.0 - 2.4 | 1.51 | 0.38 | 1.7 - 4.5 | 1.50 | 0.15 |
| *Spartina cynosuroides* (Giant Cordgrass) | Stem | 300 | 0.6 - 2.4 | 1.34 | 0.35 | 0.6 - 3.9 | 1.50 | 0.60 |
| | Leaves | 25 | 0.6 - 2.6 | 1.28 | 0.47 | 0.6 - 1.6 | 0.50 | 0.30 |
| *Spartina alterniflora* (Smooth Cordgrass) | Stem | 100 | 0.5 - 1.7 | 1.09 | 0.23 | 0.6 - 1.6 | 1.60 | 0.23 |
| | Leaves | 25 | 0.9 - 2.1 | 1.22 | 0.27 | 1.2 - 2.1 | 1.50 | 0.15 |
| *Typha latifolia* (Broadleaf Cattail) | Stem | 175 | 0.4 - 2.2 | 1.23 | 0.34 | 0.7 - 2.6 | 1.50 | 0.38 |
| | Leaves | 100 | 0.4 - 2.0 | 1.04 | 0.32 | 0.5 - 2.2 | 1.13 | 0.38 |
| *Cladium jamaicense* (Sawgrass) | Stem | 150 | 0.4 - 2.7 | 0.92 | 0.41 | 0.5 - 2.8 | 1.43 | 0.45 |
| | Leaves | 100 | 0.4 - 1.8 | 0.92 | 0.30 | 0.5 - 2.2 | 1.05 | 0.38 |
| *Juncus roemerianus* (Black Needlerush) | Culm | 225 | 0.7 - 4.3 | 1.48 | 0.42 | 0.6 - 4.1 | 1.35 | 0.30 |
| *Scirpus olneyi* (Bulrush) | Culm | 50 | 0.5 - 1.4 | 0.74 | 0.17 | 0.5 - 1.5 | 0.75 | 0.30 |

Table 6. Comparative fiber dimensions of some non-wood plants[1] and woody plants[2] in general

| Plants | Length (mm) | Diameter (μm) |
|---|---|---|
| Stem Fibers: | | |
| *Oryza* sp. (Rice) | 1.5 | 5 - 14 |
| *Phyllostachys bambusoides* (Bamboo) | 2.7 - 4.3 | 40 - 65 |
| *Saccharum officinarum* (Sugarcane) | 0.8 - 1.4 | 34 |
| *Sorghum sp.* (Sorghum) | 0.4 - 0.9 | 60 - 100 |
| *Stipa tenacissima* (Esparto grass) | 1.1 - 1.5 | 9 - 13 |
| *Triticum sp.* (Wheat) | - | 9 - 24 |
| *Zea mays* (Corn) | 0.3 - 0.6 | 24 |
| *Cyperus papyrus* (Papyrus)[3] | 1.0 - 1.8 | 0.5 - 1.0 |
| Bark Fibers: | | |
| *Boehmeria nivea* (Ramie) | 120 | 50 |
| *Cannabis sativa* (Hemp) | 20 | 22 |
| *Crotalaria juncea* (Sunn hemp) | - | 10 - 20 |
| *Gossypinus herbeceum* (Cotton stalk) | 10 - 25 | - |
| *Hibiscus cannabinus* (Kenaf) | 0.5 - 0.7 | 15 - 25 |
| *Hibiscus esculentus* (Okra) | 0.3 - 0.8 | 50 - 170 |
| Leaf Fibers: | | |
| *Agave sisalina* (Sisal) | - | - |
| *Musa textilis* (Abaca)[4] | 4 - 6 | 17 - 21 |
| Woody Plant Fibers: | | |
| Coniferous woods | 2.7 - 4.6 | 32 - 43 |
| Deciduous woods | 0.7 - 1.6 | 20 - 40 |

[1]Compiled from TAPPI Manual No. T259 os 78.

[2]From Ibrahim and Fouad 1973.

[3]From de la Cruz, Unpublished.

[4]From Malcolm 1975.

Table 7. Combustible organics (ash-free dry weight in %) and caloric content (Kcal/g) of dead wetland plants investigated. All values are mean of 6 to 12 replicates; numbers in parentheses are standard deviation.

| Plant Species | Ash-free dry wt.(%) | Calorie (Kcal/g) |
|---|---|---|
| Phragmites communis | 94.95 (2.1) | 4.43 (0.10) |
| Spartina cynosuroides | 93.74 (1.8) | 4.35 (0.09) |
| Spartina alterniflora | 92.66 (1.5) | 4.33 (0.11) |
| Typha latifolia | 93.04 (0.3) | 4.34 (0.05) |
| Cladium jamaicense | 95.18 (0.2) | 4.60 (0.07) |
| Juncus roemerianus | 96.54 (0.8) | 4.59 (0.08) |
| Scirpus olneyi | 93.14 (1.9) | 4.35 (0.18) |

Paper Strength Properties

The tear, burst, fold, and tensile strength properties of paper sheets made from pulps of the seven marsh plants are summarized in Table 8. In general, the leaves of Phragmites and Typha showed the highest values for the four strength tests. The leaves of the two species of Spartina, Juncus and Scirpus also demonstrated high tensile strength. The tensile strength of all the seven marsh species indeed, showed twice (Phragmites and S. cynosuroides stem pulp), four times (e.g., S. alterniflora and Typha stem pulp), and one order of magnitude (leaf pulp in general) higher than the tensile strength of paper specimens made from loblolly pine pulp. The tearing strength of marsh plant papers is comparable with that of pine and recycled paper. With the exception of Phragmites and S. cynosuroides stem pulps, all the other marsh plant pulps had higher burst factor value than pine or recycled paper. Due to mechanical problems experienced with the Fold Endurance Tester (the oscillating head clamp was damaged), all the materials exhibiting woody-like texture (pine, recycled paper, Phragmites, and Spartina spp.) showed very poor folding endurance. The leaves of Phragmites, Typha, Juncus, and Scirpus however exhibited good folding quality. The comparative data in Table 8 indicates that the strength qualities of marsh plant paper are equal to and, in some instances, better than those of a soft wood pulp or the recycled kraft from woody pulp.

The paper strength properties of pine kraft, recycled paper and the 50:50 blend of these two materials were comparable (Table 9). Mixing either one of these pulps with marsh plant pulp will reveal the value of the latter as supplementary source of pulp to increase bulk of wood pulp or to improve the paper qualities of recycled pulp. In

Table 8. Comparison of paper strength properties of marsh plants

| Plant Species/Part | Tear (g/mm) | Burst ($kN/m^2/mm$) | Fold (No./mm) | Tensile ($kN/m^2/mm$) |
|---|---|---|---|---|
| Pine Kraft | 254 | 224 | 1.0 | 1564 |
| Recycled Paper | 255 | 284 | 6.0 | 1515 |
| *Phragmites* Stem | 229 | 190 | 2.0 | 3414 |
| *Phragmites* Leaves | 1077 | 379 | 1043.0 | 13140 |
| *Spartina cynosuroides* Stem | 206 | 192 | 0.1 | 3653 |
| *Spartina cynosuroides* Leaves | 291 | 459 | 17.0 | 10433 |
| *Spartina alterniflora* Stem | 259 | 443 | 0.4 | 7654 |
| *Spartina alterniflora* Leaves | 294 | 516 | 10.0 | 11326 |
| *Typha* Stem | 298 | 378 | 215.8 | 5906 |
| *Typha* Leaves | 399 | 888 | 310.0 | 17418 |
| *Cladium* Culm | 195 | 320 | 0.2 | 3290 |
| *Juncus* Culm | 289 | 582 | 341.0 | 9722 |
| *Scirpus* Culm | 361 | 810 | 150.0 | 24889 |

Table 9. Strength properties of paper made from loblolly pine, recycled paper, and an equal blend of these two kraft pulps. All values are mean of 3 to 7 replicates ± standard deviation.

| Kraft Pulp | Thickness (mm) | Tear[1] (g) | Burst[2] ($kN/m^2$) | Fold[3] (No. d.f.) | Tensile[4] $kN/m^2$ |
|---|---|---|---|---|---|
| Pine Kraft | 1.5 ± 0.08 | 381 ± 53 | 336 ± 29 | 2 ± 0.7 | 2347 ± 207 |
| Recycled Paper | 1.6 ± 0.15 | 408 ± 47 | 455 ± 47 | 10 ± 2.8 | 2424 ± 549 |
| Pine and Recycled Paper (1:1 blend) | 1.5 ± 0.17 | 395 ± 81 | 429 ± 102 | 4 ± 1.8 | 2504 ± 712 |

[1]Amount of force in gram

[2]Force in kilonewton per square meter of surface

[3]Number of doublefolds

[4]Force in kilonewton per square meter of cross section

general, the blending of woody pulp and marsh plant pulp produced papers stronger than sheets molded from either pine or recycled paper alone. In some cases, the blended papers were stronger than papers made from marsh plant pulp only. The strength properties of each marsh plant species are discussed below:

*Phragmites communis*. Pulp from leaves of common reed produced strong paper in terms of folding endurance (1043 d.f./mm), tearing (1076 g/mm) and tensile (13140 $kN/m^2/mm$) strength (Table 10). There was about 100% reduction in these strength properties when leaf pulp was blended with pine kraft at the rate of 1 part pulp to 2 parts pine. Stem pulp of reed had better tensile strength (3414 $kN/m^2/mm$) than pine (1564 $kN/m^2/mm$) or recycled paper (1575 $kN/m^2/mm$), but lower tear and burst value. Stem pulp blended (1:2) with pine or recycled pulp doubled the tear and burst strength respectively. The folding endurance (2 d.f./mm) of stem pulp was very poor and the mixture with pine or recycled paper (both with poor folding strength also) did not improve folding strength. This indicated certain fiber quality in the woody pulp which is shared by *Phragmites*.

*Spartina cynosuroides*. Like *Phragmites*, *S. cynosuroides* leaf pulp showed high strength properties, except folding endurance which was very low (Table 11). When mixed with pine kraft, the tensile strength decreased dramatically (from 10432 to 3189 $kN/m^2/mm$) but folding quality increased (from 17 to 88 double folds per millimeter thickness d.f.). The stem pulp was similar to *Phragmites* in strength properties and a 1:2 blend with pine or recycled kraft did not appreciably increase the strength values over the pure *Spartina* stem pulp.

Table 10. Strength properties of paper made from the pulp of the common reed *Phragmites communis*. All values are mean of 3 to 7 replicates ± standard deviation.

| Pulp & Blend | Thickness (mm) | Tear (g) | Burst ($kN/m^2$) | Fold (No. d.f.) | Tensile ($kN/m^2$) |
|---|---|---|---|---|---|
| *Phragmites* stem (100%) | 1.3 ± 0.07 | 298 ± 21 | 248 ± 37 | 3 ± 0.5 | 4438 ± 1013 |
| *Phragmites* leaves (100%) | 0.9 ± 0.06 | 969 ± 46 | 341 ± 55 | 939 ± 137 | 11826 ± 1115 |
| *Phragmites* stem and Pine Kraft (1:2) | 1.4 ± 0.10 | 621 ± 281 | 299 ± 48 | 6 ± 0.9 | 2671 ± 299 |
| *Phragmites* stem and Recycled Paper (1:2) | 1.5 ± 0.18 | 409 ± 34 | 470 ± 54 | 41 ± 13 | 3571 ± 634 |
| *Phragmites* leaves and Pine Kraft (1:2) | 1.3 ± 0.10 | 461 ± 23 | 506 ± 20 | 79 ± 15 | 4888 ± 257 |

Table 11. Strength properties of paper made from the pulp of the giant cordgrass *Spartina cynosuroides*. All values are mean of 3 to 7 replicates ± standard deviation.

| Pulp & Blend | Thickness (mm) | Tear (g) | Burst ($kN/m^2$) | Fold (No. d.f.) | Tensile ($kN/m^2$) |
|---|---|---|---|---|---|
| *S. cynosuroides* stem (100%) | 1.3 ± 0.07 | 268 ± 8.2 | 250 ± 45 | 0.12 ± 0.01 | 4749 ± 251 |
| *S. cynosuroides* leaves (100%) | 1.1 ± 0.06 | 320 ± 4.6 | 505 ± 17 | 19 ± 5 | 11476 ± 2347 |
| *S. cynosuroides* stem and Pine Kraft (1:2) | 1.4 ± 0.09 | 393 ± 47 | 382 ± 24 | 2 ± 0.5 | 3400 ± 459 |
| *S. cynosuroides* stem and recycled paper (1:2) | 1.5 ± 0.15 | 500 ± 89 | 464 ± 88 | 12 ± 5 | 4678 ± 766 |
| *S. cynosuroides* stem and *Phragmites* stem (1:1) | 1.3 ± 0.09 | 269 ± 25 | 221 ± 28 | 0.21 ± 0.1 | 4562 ± 810 |
| *S. cynosuroides* leaves and Pine Kraft (1:2) | 1.4 ± 0.09 | 458 ± 43 | 434 ± 36 | 123 ± 62 | 4465 ± 805 |

*Spartina alterniflora*. Except for tensile value (11326 vs. 7654 $kN/m^2/mm$), the strength properties of leaf pulp and stem pulp were the same (Table 12). When blended with pine and recycled paper pulp, *Spartina* pulp quality increased especially the folding endurances, but the tensile value decreased. A 1:1 blend of *Spartina* and *Phragmites* stem pulps showed no apparent improvement in the qualities of either one (Table 10). Blended stem pulp also decreased in tensile property compared to pure *S. alterniflora* stem, but resistance to creasing of folding dramatically increased by two orders of magnitude.

*Typha latifolia*. The paper quality of this cattail is characterized by very strong folding endurance (6000 to 17000 d.f./mm) (Table 13). Both leaf and stem pulps when blended with pine kraft and recycled paper at 1:2 and with *Phragmites* pulp at a 1:1 ratios increased the folding strength of the woody and reed pulps by one order of magnitude from <10 to >900 double folds. *Typha* pulp also increased the tear, burst, and tensile strengths of pine and recycled pulp when these were mixed with *Typha*.

*Cladium jamaicense*. The stem pulp of this sedge species generally increased in strength properties when blended with pine pulp, recycled paper, and *Typha* stem pulp (Table 14). By itself, sawgrass paper is comparable to the other marsh grass paper in strength qualities. The folding endurance remained very low whether alone or blended.

*Juncus roemerianus* and *Scirpus olneyi*. These two plants, a rush and a sedge, are rhizomatous plants characterized by underground stems. The shoots used for pulping were basically all leaves. As shown already by the other plants analyzed, leaf-pulp generally showed high folding and tensile strengths. As can be seen in Tables 15 and 16, folding

Table 12. Strength properties of paper made from the pulp of the smooth cordgrass *Spartina alterniflora*. All values are mean of 3 to 7 replicates ± standard deviation.

| Pulp & Blend | Thickness (mm) | Tear (g) | Burst (kN/m$^2$) | Fold (No. d.f.) | Tensile (kN/m$^2$) |
|---|---|---|---|---|---|
| *S. alterniflora* stem (100%) | 1.0 ± 0.13 | 259 ± 12 | 443 ± 124 | 0.36 ± 0.23 | 7654 ± 1698 |
| *S. alterniflora* leaves (100%) | 0.9 ± 0.06 | 265 ± 80 | 465 ± 35 | 9.36 ± 6.03 | 10193 ± 896 |
| *S. alterniflora* stem and Pine Kraft (1:2) | 1.2 ± 0.11 | 420 ± 17 | 427 ± 31 | 325 ± 87 | 6992 ± 835 |
| *S. alterniflora* stem and recycled paper (1:2) | 1.5 ± 0.22 | 593 ± 68 | 541 ± 105 | 490 ± 284 | 5059 ± 637 |
| *S. alterniflora* stem and *Phragmites* stem (1:1) | 1.0 ± 0.08 | 295 ± 60 | 404 ± 41 | 0.2 ± 0.05 | 6775 ± 1150 |
| *S. alterniflora* leaves and Pine Kraft (1:2) | 1.2 ± 0.09 | 451 ± 55 | 516 ± 70 | 287 ± 89 | 5835 ± 1190 |

Table 13. Strength properties of paper made from the pulp of the broadleaf cattail *Typha latifolia*. All values are mean of 3 to 7 replicates ± standard deviation.

| Pulp & Blend | Thickness (mm) | Tear (g) | Burst (kN/m$^2$) | Fold (No. d.f.) | Tensile (kN/m$^2$) |
|---|---|---|---|---|---|
| *Typha* stem (100%) | 1.2 ± 0.07 | 358 ± 36 | 454 ± 58 | 259 ± 120 | 7087 ± 845 |
| *Typha* leaves (100%) | 1.0 ± 0.04 | 399 ± 6 | 888 ± 60 | 310 ± 70 | 17418 ± 1582 |
| *Typha* stem and Pine Kraft (1:2) | 1.4 ± 0.08 | 498 ± 61 | 454 ± 58 | 211 ± .07 | 4642 ± 1110 |
| *Typha* stem and recycled paper (1:2) | 1.4 ± 0.09 | 502 ± 48 | 471 ± 61 | 978 ± 1.07 | 5789 ± 1256 |
| *Typha* stem and *Phragmites* stem (1:1) | 1.2 ± 0.10 | 307 ± 29 | 353 ± 37 | 64 ± 23 | 5780 ± 1501 |
| *Typha* leaves and Pine Kraft (1:2) | 1.3 ± 0.07 | 516 ± 55 | 563 ± 34 | 1984 ± 34 | 8477 ± 957 |

Table 14. Strength properties of paper made from the pulp of the sawgrass *Cladium jamaicense*. All values are mean of 3 to 7 replicates ± standard deviation.

| Pulp & Blend | Thickness (mm) | Tear (g) | Burst ($kN/m^2$) | Fold (No. d.f.) | Tensile ($kN/m^2$) |
|---|---|---|---|---|---|
| *Cladium* stem (100%) | 1.6 ± 0.10 | 312 ± 56 | 513 ± 46 | 0.25 ± 0.1 | 5264 ± 867 |
| *Cladium* stem and Pine Kraft (1:2) | 1.9 ± 0.10 | 623 ± 13 | 522 ± 56 | 13 ± 1.0 | 6456 ± 141 |
| *Cladium* stem and recycled paper (1:2) | 2.0 ± 0.30 | 584 ± 24 | 853 ± 103 | 8 ± 0.6 | 5108 ± 4 |
| *Cladium* stem and *Typha* stem (1:1) | 1.7 ± 0.20 | 452 ± 33 | 576 ± 43 | 1.5 ± 0.5 | 10582 ± 764 |

Table 15. Strength properties of paper made from the pulp of the black needlerush *Juncus roemerianus*. All values are mean of 3 to 7 replicates ± standard deviation.

| Pulp & Blend | Thickness (mm) | Tear (g) | Burst ($kN/m^2$) | Fold (No.d.f.) | Tensile (kN/m2) |
|---|---|---|---|---|---|
| *Juncus* culm (100%) | 1.1 ± 0.08 | 318 ± 50 | 640 ± 50 | 375 ± 259 | 10694 ± 1969 |
| *Juncus* culm and Pine Kraft (1:2) | 1.3 ± 0.07 | 468 ± 32 | 488 ± 44 | 244 ± 84 | 4660 ± 759 |
| *Juncus* culm and recycled paper (1:2) | 1.4 ± 0.15 | 530 ± 37 | 605 ± 25 | 325 ± 249 | 6298 ± 633 |
| *Juncus* culm and *Phragmites* stem (1:1) | 1.2 ± 0.09 | 317 ± 30 | 462 ± 47 | 42 ± 18 | 8177 ± 1026 |

Table 16. Strength properties of paper made from pulp of the bulrush *Scirpus olneyi*. All values are mean of 3 to 7 replicates ± standard deviation.

| Pulp & Blend | Thickness (mm) | Tear (g) | Burst ($kN/m^2$) | Fold (No. d.f.) | Tensile ($kN/m^2$) |
|---|---|---|---|---|---|
| *Scirpus* culm (100%) | 0.7 ± 0.10 | 253 ± 22 | 567 ± 48 | 105 ± 9 | 17422 |
| *Scirpus* culm and Pine Kraft (1:2) | 1.1 ± 0.09 | 491 ± 34 | 638 ± 53 | 656 ± 280 | 9627 ± 1793 |
| *Scirpus* culm and recycled paper (1:2) | 1.2 ± 0.09 | 589 ± 58 | 703 ± 30 | 819 ± 346 | 10319 ± 1373 |
| *Scirpus* culm and *Phragmites* stem (1:1) | 0.9 ± 0.06 | 290 ± 32 | 525 ± 41 | 23 ± 15 | 14062 ± 890 |

endurance was high except when blended with Phragmites stem pulp. Tensile property was also high in both plants but diminished when blended with pine, recycled paper, or Phragmites stem pulp. Their tearing and bursting properties were also comparatively higher than the other marsh plants and pine (Table 8). It is apparent that leafy pulps do exhibit superior bonding quality which enhances the strength qualities not found in the stems.

## DISCUSSION

Of the seven marsh plants investigated, the common reed or roseau cane *Phragmites communis* and the giant or cane cordgrass *Spartina cynosuroides* had the highest percentages of recoverable pulp (37 and 32%, respectively), the highest alpha-cellulose contents (29 and 35%, respectively), and the highest concentration of six-carbon sugars (70%). These two non-wood wetland plants hold promise as raw materials for manufacture of paper, extraction of carbohydrates and other chemicals, and production of alcohol. *Phragmites* also had the largest fiber dimension (1.0 to 3.3 mm length and 2.3 to 14.3 μm width) which is the primary basis of the strength qualities of the manufactured paper. Fiber length, for instance, is the most important factor influencing tear strength. Longer fibers tend to distribute the stress over a greater area, involving more fibers and more bonds. On the other hand, short fibers allow the stress to be concentrated in a smaller area resulting in low tear strength.

The other marsh plants, while they exhibited lower pulp contents and smaller fiber dimensions, the paper sheets made from them, especially from that of *Typha*, demonstrated strength properties that were better than pine kraft or recycled paper based on a constant sheet thickness. As shown in Tables 9 through 16, the thickness of paper sheets made from pine kraft and recycled paper pulp were considerably greater than the thickness of equal weight paper sheets made from the various marsh plants. The increased density of the paper made from the various marsh plant pulps indicates that the fibers in these pulps are more flexible (pack together easier) than the fibers in pine kraft pulp. The more dense packing accounts, at least in part, for the superior pulp properties of marsh plant pulp as compared to pine kraft pulp. Blending of one part marsh plant pulp to two parts softwood pulp improved the qualities of softwood pulps. Van den Ent (1975) reported that the strength properties of a mixture of hardwood pulp and bagasse (a non-wood) are more favorable than those of each of the components. Some high density hardwoods (tropical species) produce paper sheets with imbalance tear and tensile strength. Non-wood pulps in general and marsh plants in particular presumably produce paper of balanced sheet strength because of their good interfiber bonding characteristics. The so-called "interfiber bonding" is an important factor in the strength qualities of paper. Low interfiber bonding gives low tear because the fibers pull apart easily. The degree of interfiber bonding is also of predominant importance in the burst and tensile strength of paper. Villavicencio (1971) found the strength properties of sugarcane bagasse (tear = 358 g/mm; burst = 29,300 $kN/m^2/mm$; fold = 64/mm; tensile = 4405 $kN/m^2/mm$) to be better than commercial newsprint from wood. Likewise, Malcolm (1975) reported that the tensile, tear, and burst qualities of abaca, which has longer fibers than spruce wood (abaca = 4-6 mm versus spruce = 2-3 mm), are 100 times, 2 times, and 4 times stronger than spruce wood. The properties of the paper made from marsh plant pulp during this investigation indicates that these pulps have good to excellent interfiber bonding. The evidence for this conclusion is the superior strength properties of marsh plant pulps compared to pine kraft pulp even though the fibers in the marsh plant pulps were generally shorter than the fibers in pine kraft pulp.

The strength properties of paper are affected by (a) the individual fiber strength, (b) average fiber length, (c) interfiber bonding, and (d) the structure and formation of the paper sheet. Because all the paper sheets made during this investigation were manually pressed and dried in an ordinary laboratory oven with improvised clamps, the possibility of fiber degradation and/or poor paper formation may have reduced the strength quality of the specimens. This is especially detected by the fold endurance test. In general, the fold strength of all papers tested, including the reference specimens pine and recycled paper, was very low. We ascribe the poor folding or creasing endurance shown by the specimens (except in one case - Phragmites leaves) to the defective lower jaw clamp of the Folding Endurance Tester.

While the objective of this study was to examine the pulp characteristics and paper making potential of marsh plants, the philosophy behind our aim was to explore the feasibility of using these plants as a supplementary, not an alternative, source of raw material for paper and cellulose products. It is evident from our findings that the common reed and giant cordgrass can be pulped to increase the bulk of manufactured paper. In situations where both or either one of these plants grow in great abundance, the feasibility of them or one of them being farmed as a primary, but not the exclusive, source of paper pulp is manageable. The common reed and the giant cordgrass, as well as the other marsh plants we pulped in this project can be utilized also as blending material with wood pulp to improve texture quality or to increase certain strength property. To some extent, quality improvement can be achieved by proper blending and suitable preparation of short fiber raw materials (Van den Ent 1975). The fiber of non-wood plants are generally short. The increasing move towards paper recycling does lend itself quite appropriately to the use of non-wood short fiber pulp both for bulk and quality control of recycled paper, newsprint, and inferior wood fibers.

Obviously, the potential of commercially harnessing the wetlands of the world to produce pulp, cellulose, and other by-products is only possible in areas where wetlands hectarage will warrant a management approach to wetland farming which will insure a continuous production of raw material in tonnage quantities that will support a profitable enterprise. For now, this venture is attractive only to countries where forest resources is either wanting or in short supply. However, the prognosis for the near future is a worldwide tightening of pulpwood supply, and the most viable alternative is the utilization of non-wood plants.

Non-wood vegetation refers primarily, but not exclusively, to grasses both those grown for crops (grains and canes) and those that grow in the wild prairies, savannahs, and wetlands. The wetlands, particularly the marshes and swamps characterized by diurnal (i.e., tidal) or seasonal (i.e., precipitation) water fluctuation are reputed to be among the most productive natural ecosystems in the world. They are also noted as wildlife habitat, bird sanctuaries, and in some cases, as locations of fertile fisheries. Furthermore, wetlands have hydrologic and atmospheric functions of global dimension (de la Cruz 1976).

To harvest the wetlands for pulp or cellulose or alcohol may be controversial but not inconceivable. The demand for fiber resources is increasing to shortage proportions. It is inevitable that the high production capacities of the wetlands be harnessed to supply this need. The crux of the matter is conservation and the key to the wise use of this vital resource is intelligent management.

The Romanian model of reed farming seems adequate. Over a century of forest management in the United States and elsewhere provided the world with testable schemes for conservation. The experience of pulping rice straw in China, wheat straw in the Netherlands, barley in Italy, sugarcane in the Philippines, sisal in Mexico, seaweeds in Russia, bamboo in Brazil, esparto grass in Spain, sabai grass in India are definitely dictated by insufficient supply of other raw materials to meet the increasing demand for fibers in these nations. There is reason to believe that conservation will be a primary consideration in the cultural alteration of wetlands to insure sustainable yields and at the same time preserve the integrity of wetlands in order that they may continue to play their ecosystem and global functions.

## CONCLUSIONS

1. The percentage of crude pulp and cellulose yield of at least three marsh plants (the common reed *Phragmites communis*, the giant cord-grass *Spartina cynosuroides*, and broadleaf cattail *Typha latifolia*) are comparable to woody plants.

2. The length of Phragmites fibers is more than the fiber length of deciduous woody plants and comparable with that of coniferous wood.
3. The strength properties (tear, burst, and tensile) of paper made from these pulps are comparable to softwood (loblolly pine) and recycled kraft. Folding endurance is low due to a combination of factors (e.g., fiber dimension, mechanical defects, and fiber degradation due to poor paper formation) but could be increased through blending with other pulp species.
4. The pulp from the leaves of the needlerush Juncus roemerianus and the bulrush Scirpus olneyi and stem pulp of the smooth cordgrass Spartina alterniflora and the sawgrass Cladium jamaicense although of lower yield, exhibited strength quality better than woody pulp (pine and recycled paper).
5. The potential of using Phragmites, Spartina and Typha as supplementary sources of pulp exist because of their high crude pulp yield.
6. The potential of using other marsh plants with lower pulp yield as blending material with wood pulp to increase bulk and improve strength also exists.
7. The high cellulose content of Phragmites and Spartina cynosuroides also indicates the potential of these plants in the production of alcohol and other cellulosic substances.

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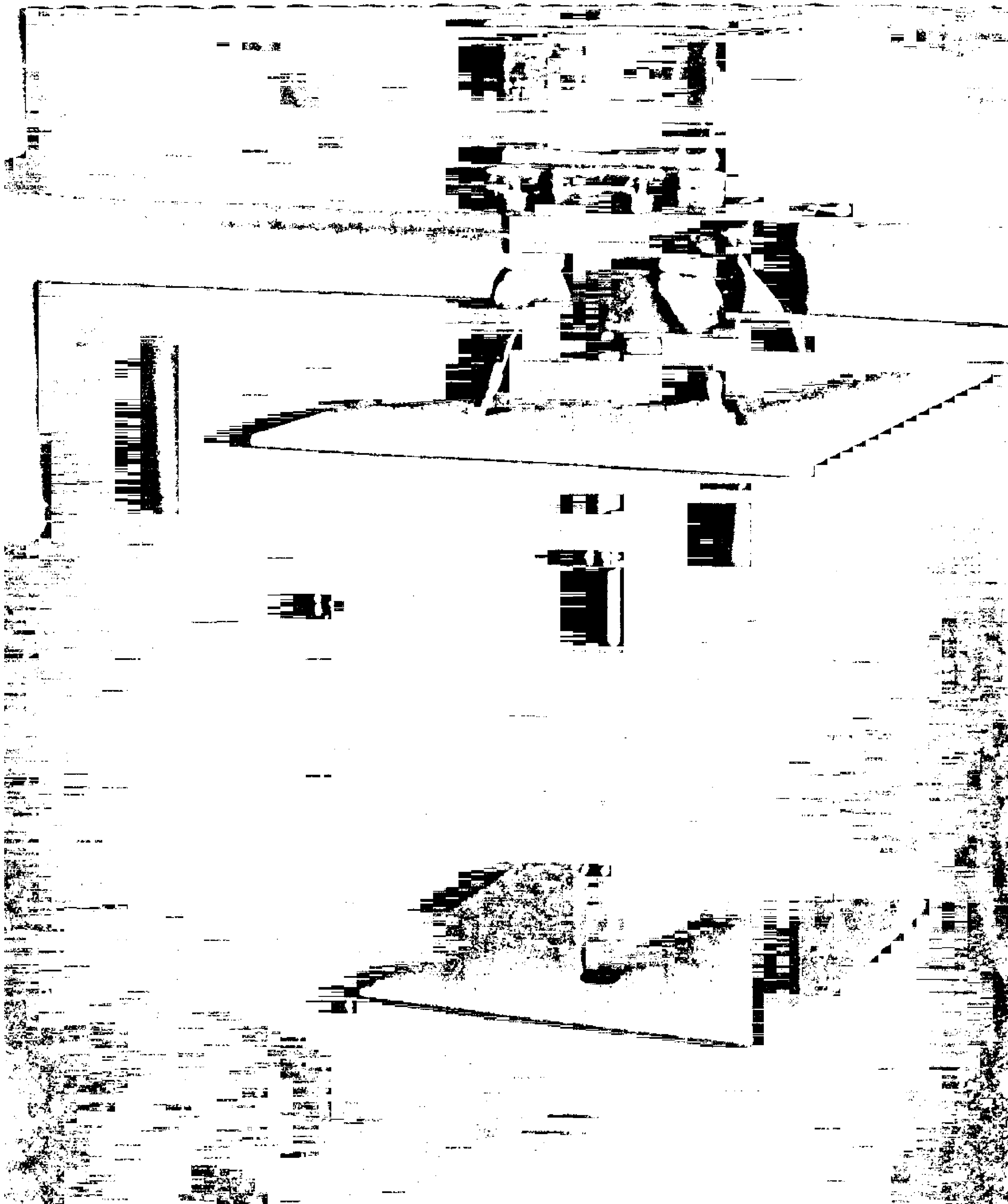
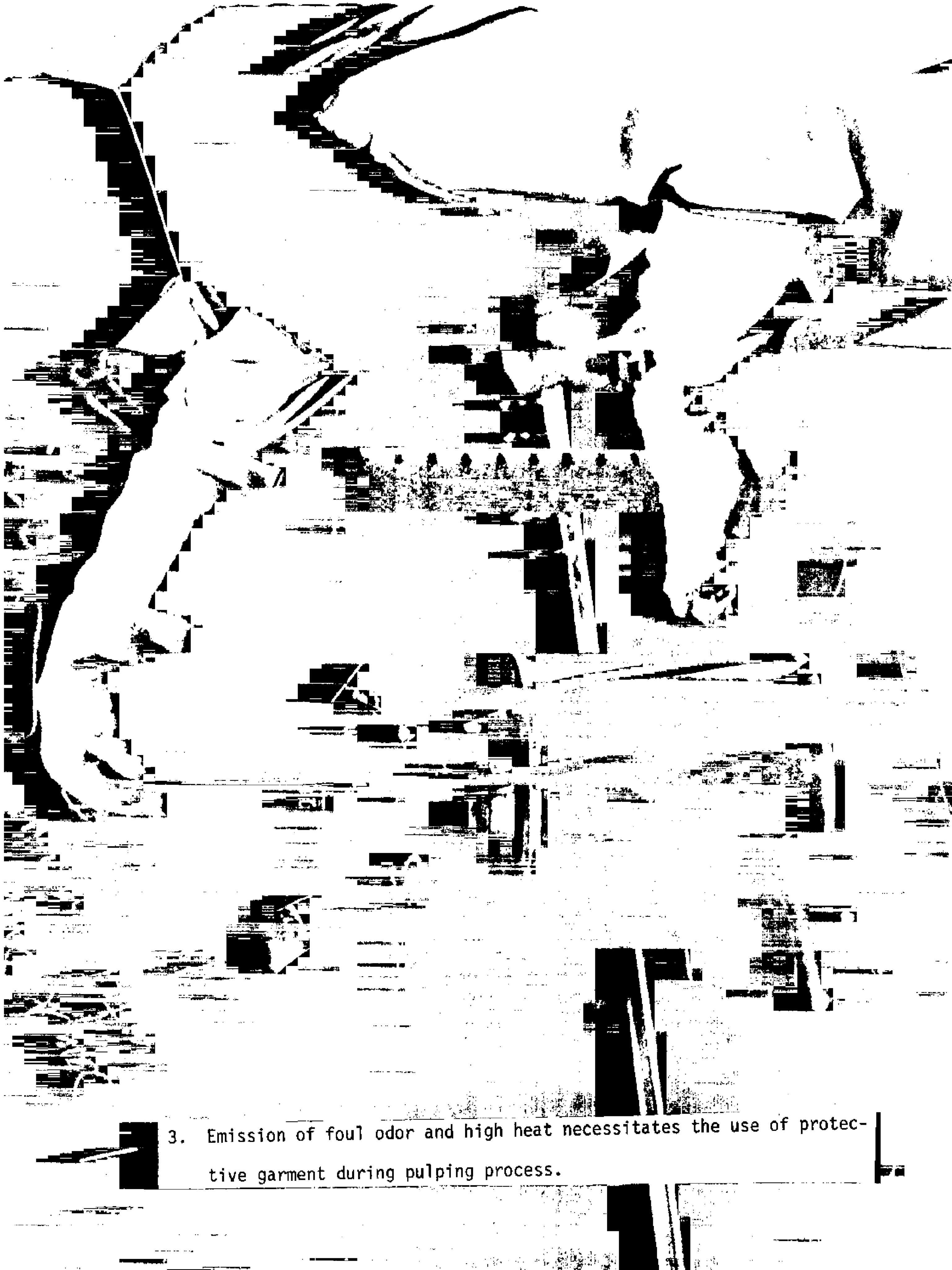
# A P P E N D I X

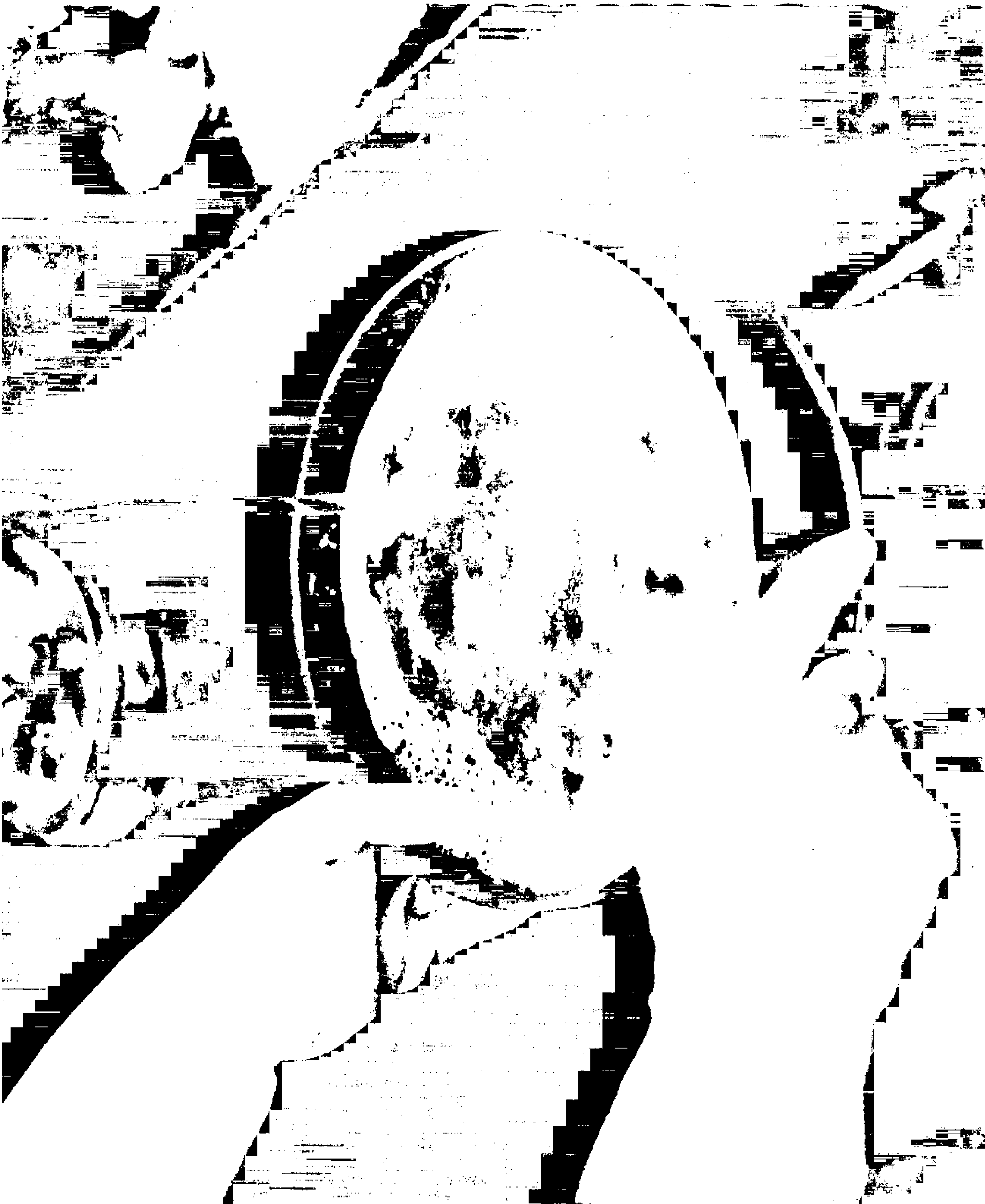


1. Williams Standard Sheet Mould with 8 x 8 inches deckle plate used in making paper sheets.

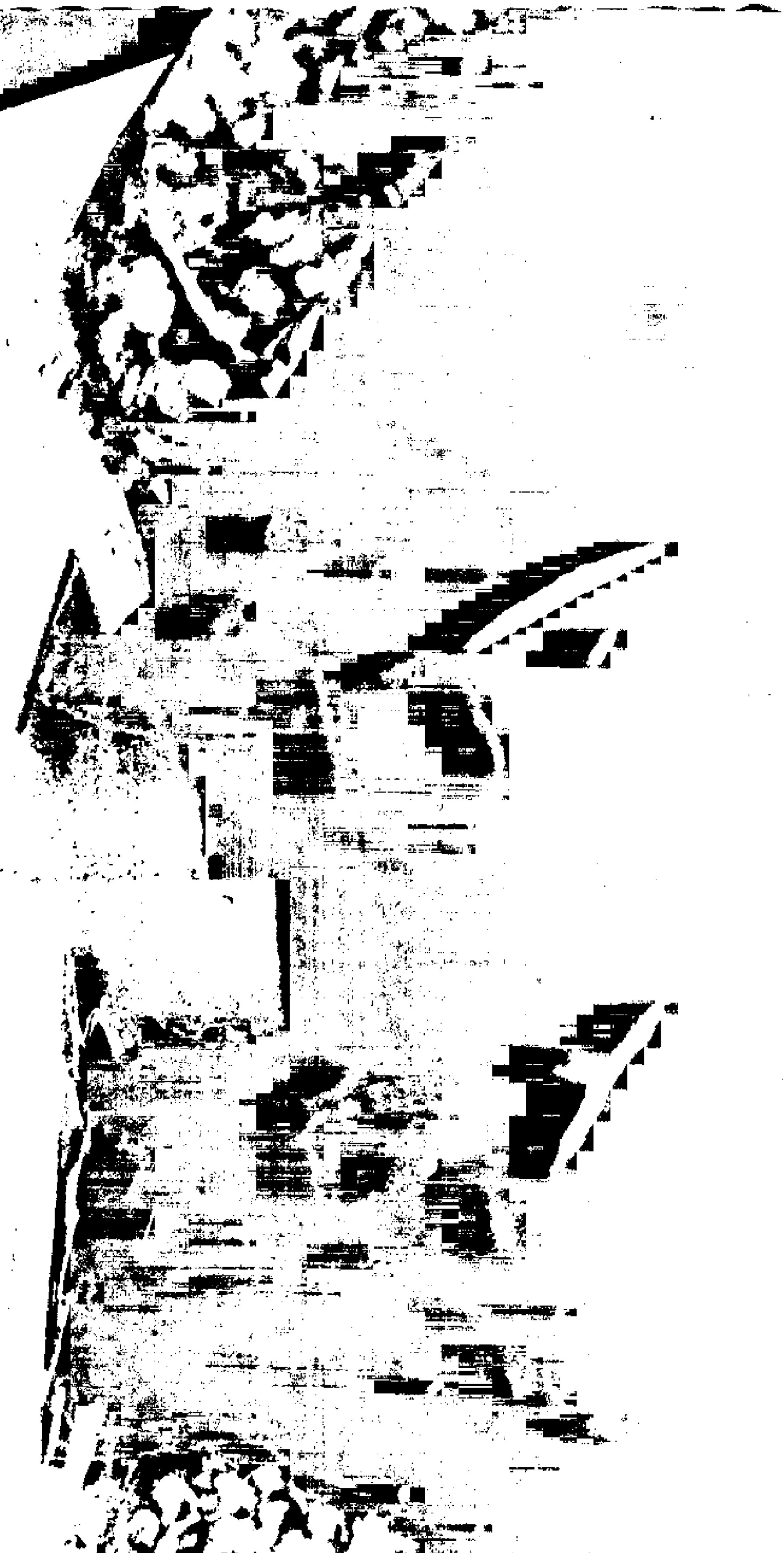
2. Close-up photograph of the leaves (top) and stems (below) of the common reed <u>Phragmites</u> communis.



3. Emission of foul odor and high heat necessitates the use of protective garment during pulping process.



4. Pulp is washed under running water over a fine mesh (144 μm) stainless steel sieve.



5. Photograph showing the raw material (chopped marsh plant), crude pulp (unbleached fiber), and finished product (paper sheet).

6. Co-investigator Geroge R. Lightsey operating the Tear Tester.

7. Principal investigator Armando A. de la Cruz showing unbleached pulp of Phragmites.