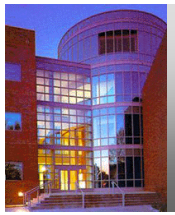


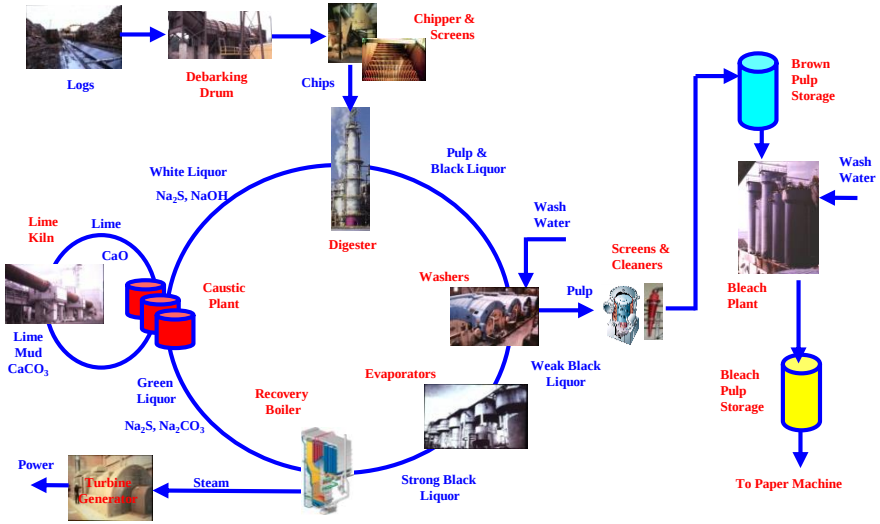
paperscience
nc state university

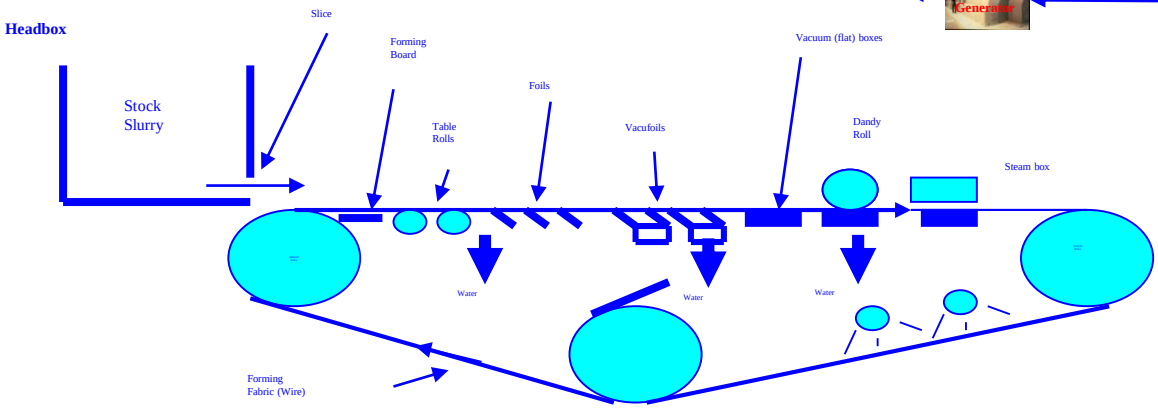
Paper Primer

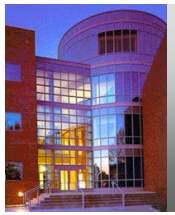
Dr. Richard Venditti
Paper Science and Engineering
NC State University
September 24, 2015

Course Objectives

1. Overview of the industry and products
2. Wood and Fiber Supply
3. Methods of Production
4. Environmental Impacts
5. Paper recycling
6. Environmental LCA



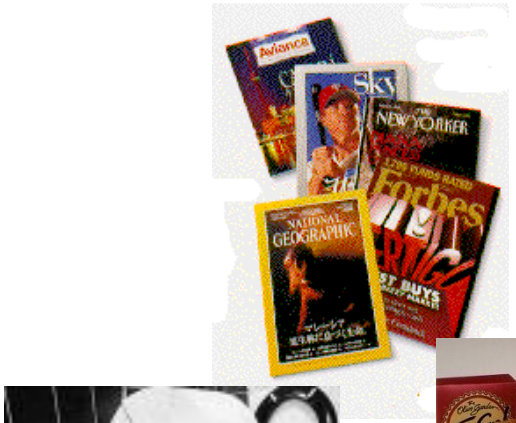




1. Overview of the industry and products

Importance of Paper

- Society vitally depends on paper products
- Paper plays an important role in so many areas of human activity
  - *Communication*
  - *Packaging*
  - *Tissue and toweling*
  - *Health Products*
  - *Filtration…….*



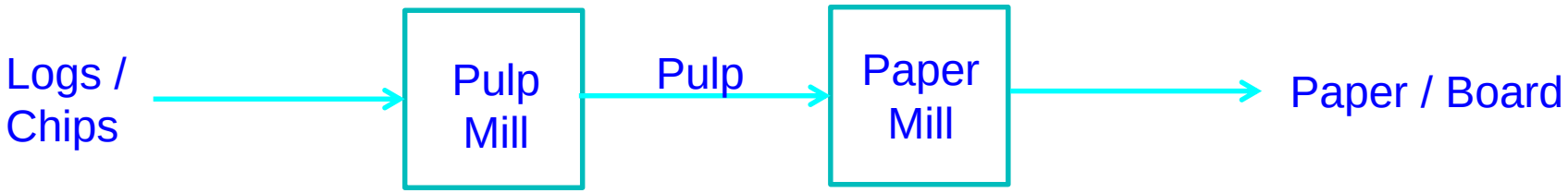
Paper History

- *The word paper is derived from from the Egyptian reedy plant PAPYRUS, whose stem was beat and pressed into thin layers (3000 BC.*
- *Paper was invented in China in 105 AD*
  - *Ability to have information on paper won wars and kept Emperors in power*
- *1100s, paper introduced to Europe*
- *1400s printing press with movable type created*
- *In the 1700- automated paper machines were created*
- *1800s kraft and mechanical pulp manufacturing*
- *1900s modern kraft pulp mills and new paper grades*

Pulp and Paper -- Definitions

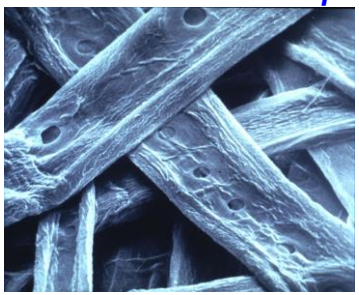
- *"Pulp" refers to the mass of fibers which results when plant material is disassembled, either mechanically or chemically*
- *Pulp is the raw material for paper*

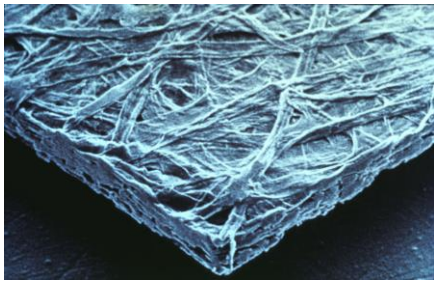
An "Integrated" Manufacturing Facility



Paper – The *Technical* Definition

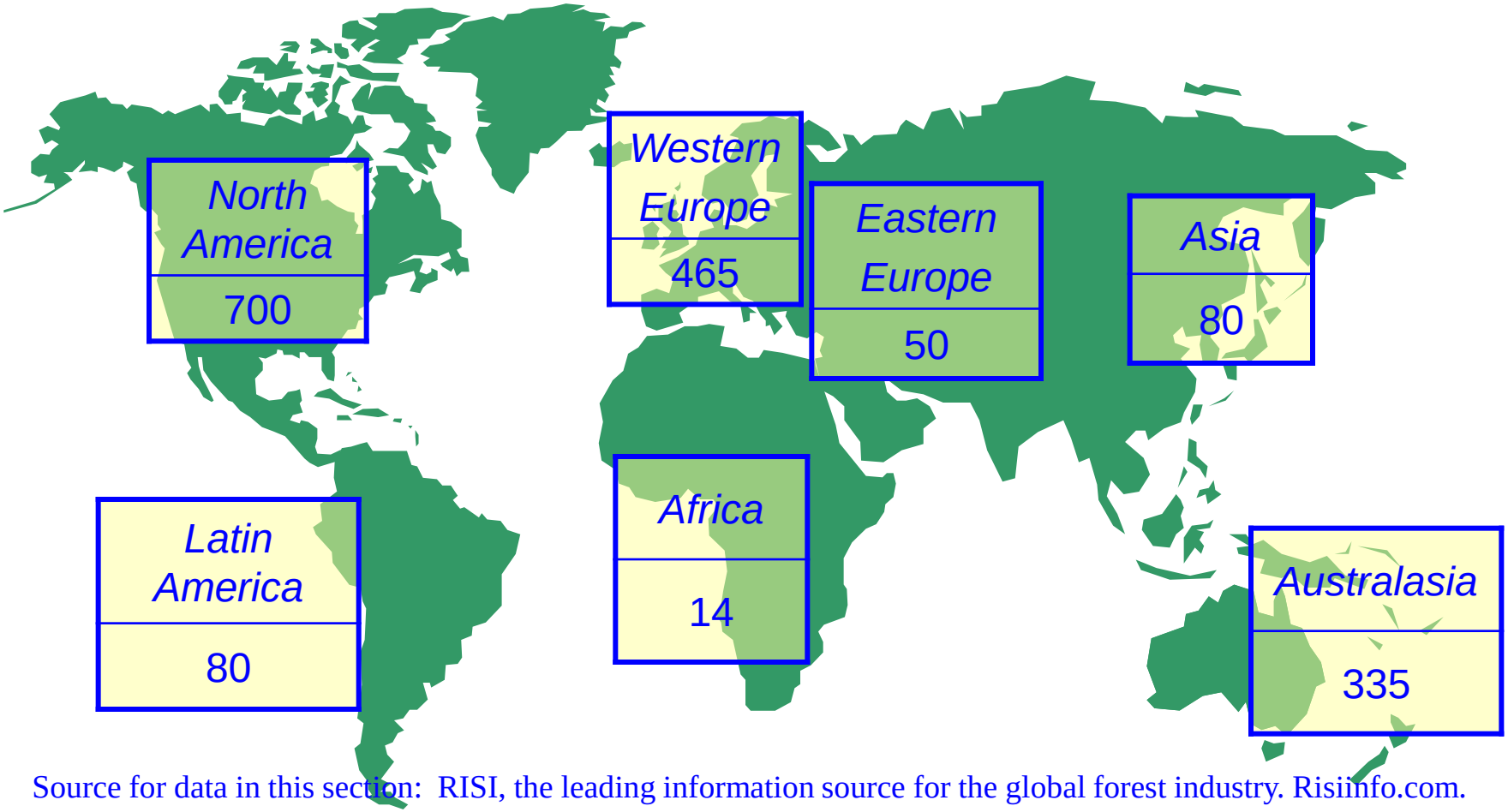
A web consisting of cellulose fibers – extracted from plants -- deposited from a water suspension and then dried to form inter-fiber ***hydrogen bonds***





CONSUMPTION OF PAPER AND BOARD, LB/PERSON (CIRCA 2010)

North America has the largest per capita demand by a large margin

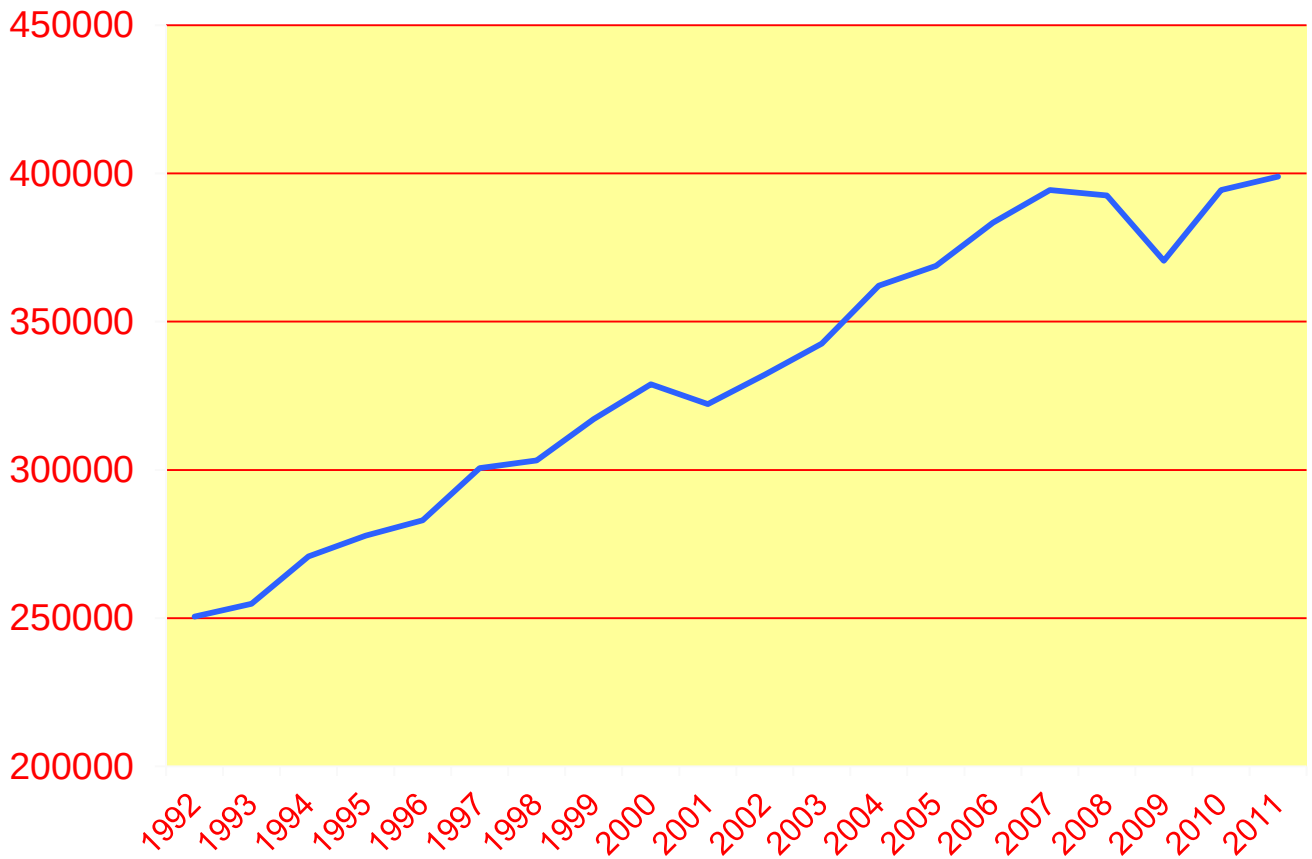


Source for data in this section: RISI, the leading information source for the global forest industry. Risiinfo.com.

Worldwide Consumption of Paper and Paperboard

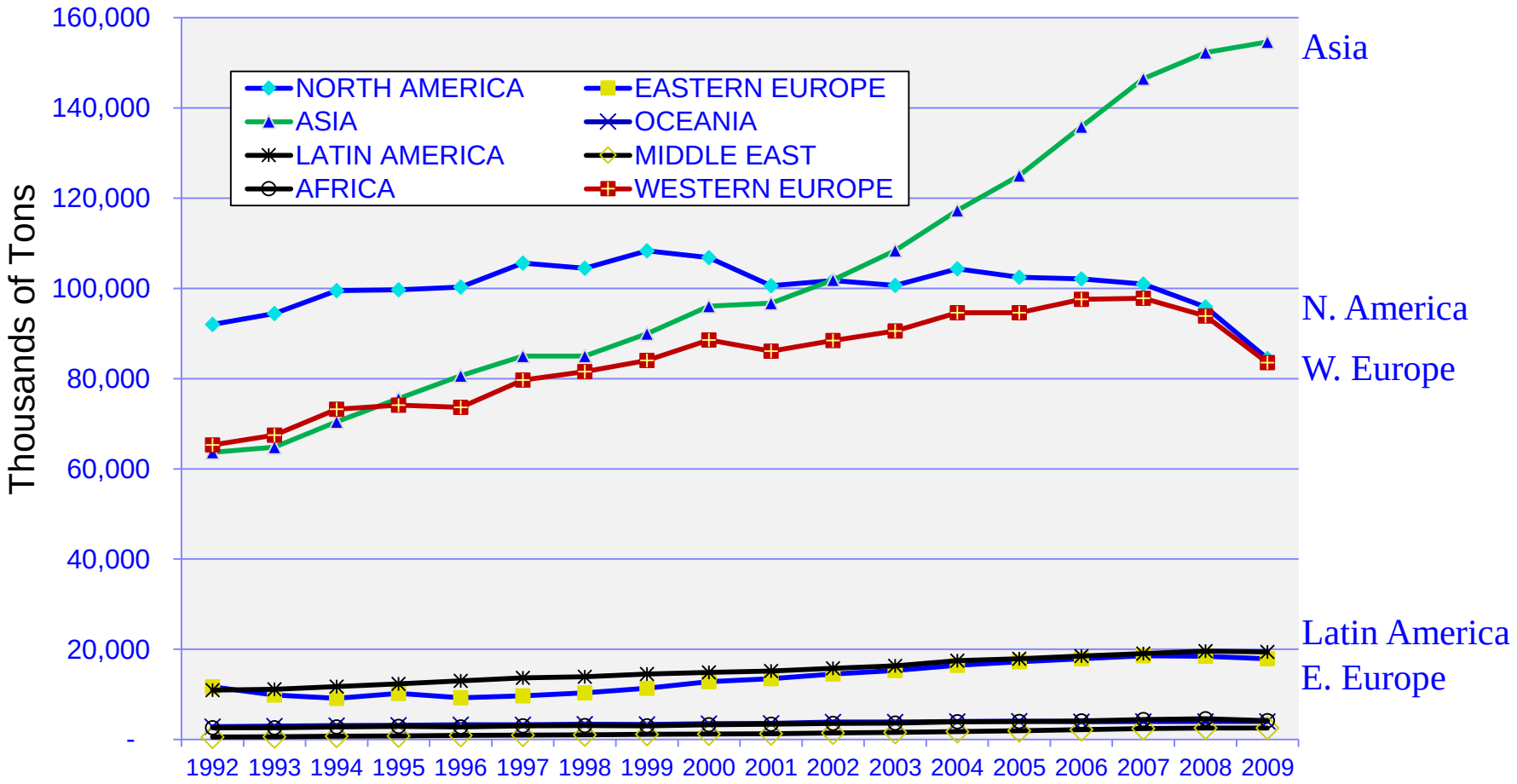
Current total consumption is about 400 million metric tons per year, roughly:

- ➔ **1 billion tons of wood**
- ➔ **20 billion tons of water**



Source: RISI

Production of Paper and Board



The World's Largest Paper and Paperboard Industries

2012 Paper & Board Global Production		
	1,000 tonnes	% of Global
1. China, People's Rep.	102,500	25.6
2. USA	74,375	18.6
3. Japan	26,083	6.5
4. Germany	22,630	5.7
5. Sweden	11,417	2.9
6. South Korea	11,333	2.8
7. Canada	10,751	2.7
8. Finland	10,694	2.7
9. Brazil	10,260	2.6
10. Indonesia	10,247	2.6

Total Global Production: 400 million metric tons

U.S. Paper & Packaging Industry	
Total sales	$115 billion
Contribution to US GDP	$ 250 billion
Total persons employed	1,300,000
Total payroll	$ 30 billion
Number of trees planted	1.5 billion
Ranking of all US industries	Top 10

Paper and Board Industry is the 4th largest in the US.

Paper Products

- Printing and Writing
  - *Newsprint*
  - *Light weight coated magazines*
  - *Coated free sheet*
  - *Bond (Copy Paper)*
- Board
  - *Carton board (multi-layered thick board)*
  - *Container board (fluted boxes…)*
  - *Specialty*
- Tissue
- Fluff Pulp
- Dissolving Pulp
- Others…

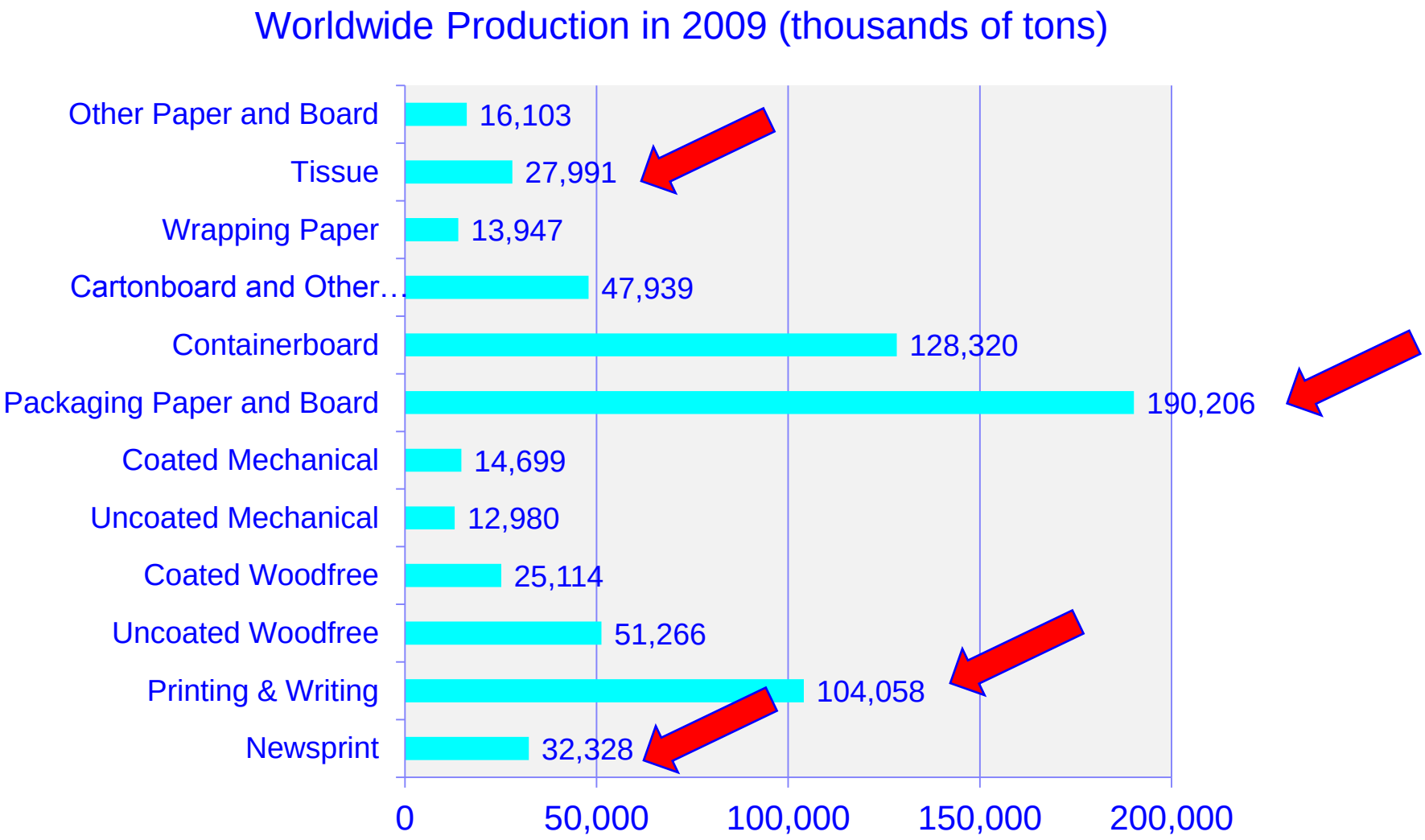
U.S. Paper and Paperboard Production

	Production 000 tons
Newsprint	3,000
Writing and Printing	18,000
Other Paper(s)	3,000
Tissue	8,000
TOTAL PAPER	**32,000**
TOTAL PAPER & BOARD	**79,000**

	Production 000 tons
Unbleached Kraft Paperboard	21,000
Solid Bleached Paperboard	5,000
Semichemical Paperboard	6,000
Recycled Paperboard	15,000
TOTAL PAPERBOARD	**47,000**
TOTAL PAPER & BOARD	**79,000**

Board is > 0.25mm

Worldwide Paperboard Production



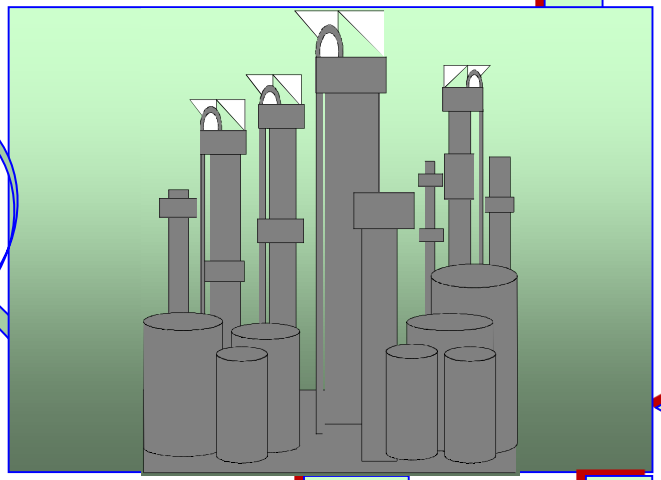
Cost of a Pulp and Paper Mill

- Modern pulp and paper mill capital cost is approximately $1 Billion Dollars for a mill that makes a million tons of paper per year.

- Extremely capital intensive
  - *Requires significant land and access to water*
  - *Large equipment to produce over 1000 tons per day*
  - *Chemical and wood handling facilities required*
  - *Energy production equipment*
  - *Gas and water treatment systems*

The Future: Forest Biorefinery

➥Pyrolysis of residues
➥Co-feed into refinery

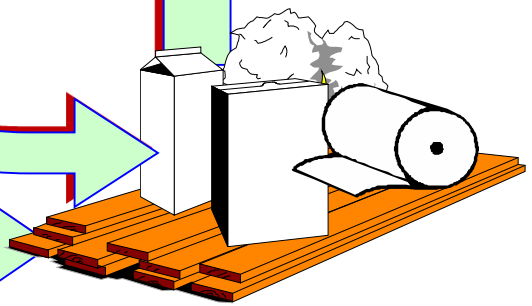


Syngas

Liquid Fuels and Chemicals from:
➥BL Gasifier, and
➥Wood Residual Gasifier

Black Liquor & Residuals

Steam, Power & Chemicals



Pulp Manufacturing

➥Extract portion of the hemicellulose
➥Convert the extract to ethanol and chemicals

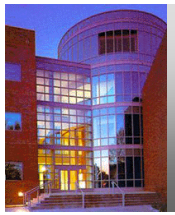
➥Cellulose used to manufacture paper
➥Cellulose used to manufacture ethanol

courtesy of:
Del Raymond (Weyerhaeuser)

Section Summary

- Paper is used in many different types of products and is an essential component of our lives
- About 400 million tons of paper produced per year, and increasing
- China and US are the leaders
- A very capital intensive industry

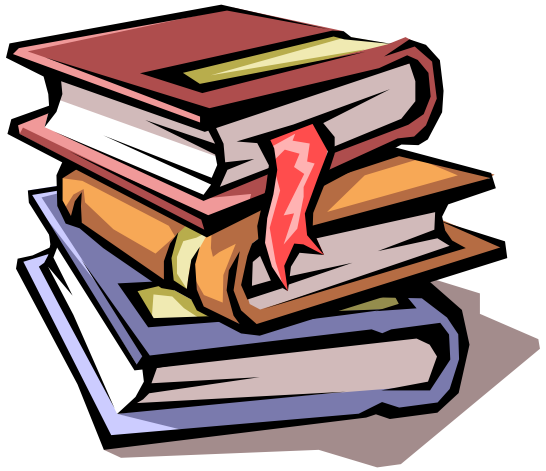
Questions?



2. Wood Supply and Fiber Supply

Section Learning Objectives

- Learn about forests
- Learn about the woodyard process
  - *debarking*
  - *chipping*
  - *chip screening*
- Learn about wood structure
  - *Hardwood*
  - *softwood*



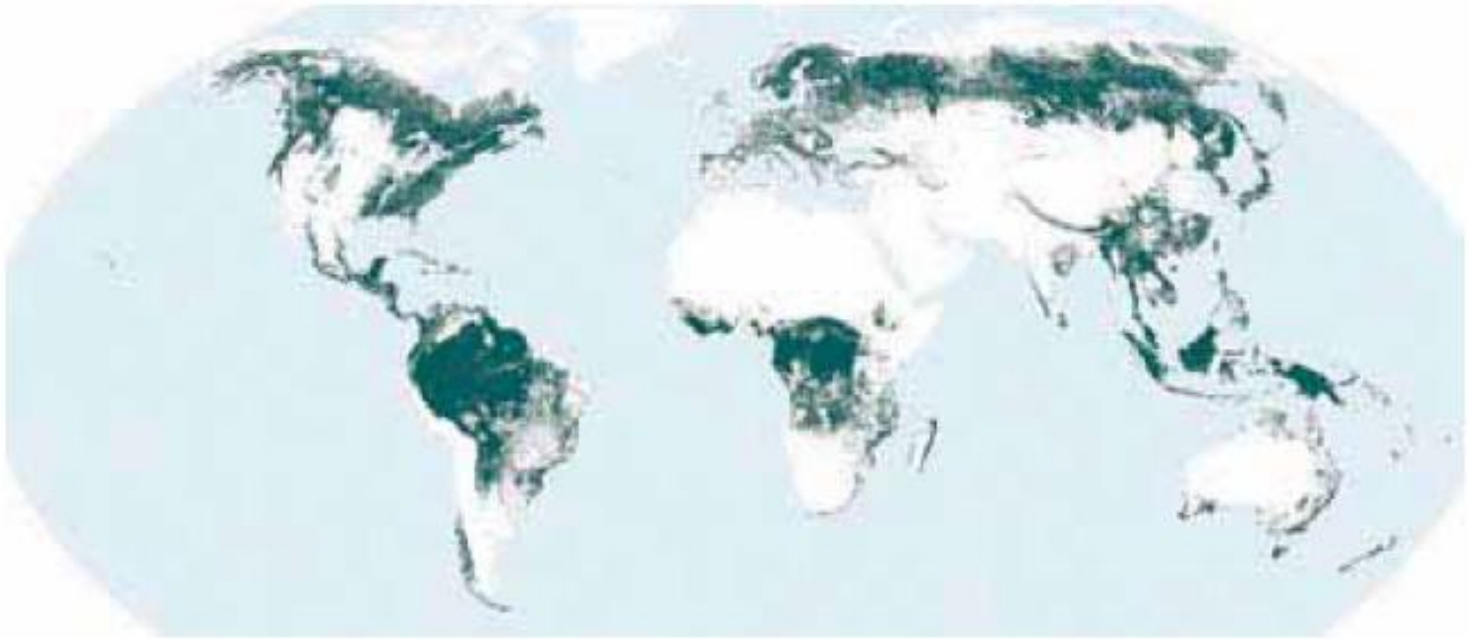
Global Forests (Food and Agricultural Organization (FOA) of the United Nations, Global Forest Resources Assessment 2010)

- *Forests cover **31% of total global land**, 4000 million hectares*
- *About **13 million hectares** of forest are converted to other uses or naturally **lost** per year, S. America and Africa dominate losses*
  - *Fires, pest, disease, invasive species impact forests*

- ***Net changes** of forest area are about **-5.2 million hectares** per year*
- *World forests **store 289 gigatonnes of carbon**, decreasing by about 0.5 Gt per year*

- ***36%** of forests are primary, native **undisturbed***
- ***13%** are **protected** areas*
- ***30%** of forests are primarily used for **forest products***
- *Forests are managed for many different reasons*

FIGURE 1
The world's forests



Note: Tree cover derived from MODIS VCF* 250 meter pixels for year 2005.

* Moderate-resolution Imaging Spectroradiometer Vegetation Continous Fields (Hansen *et al.* 2010).

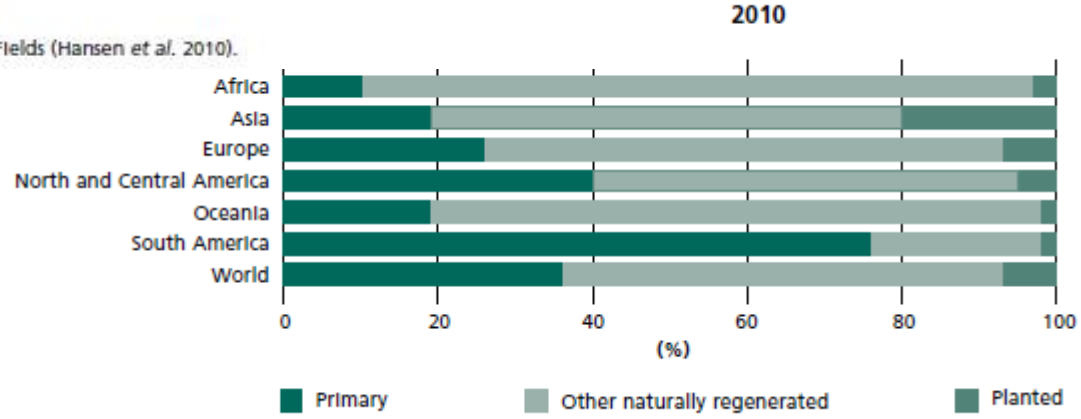


FIGURE 4

Annual change in forest area by region, 1990–2010

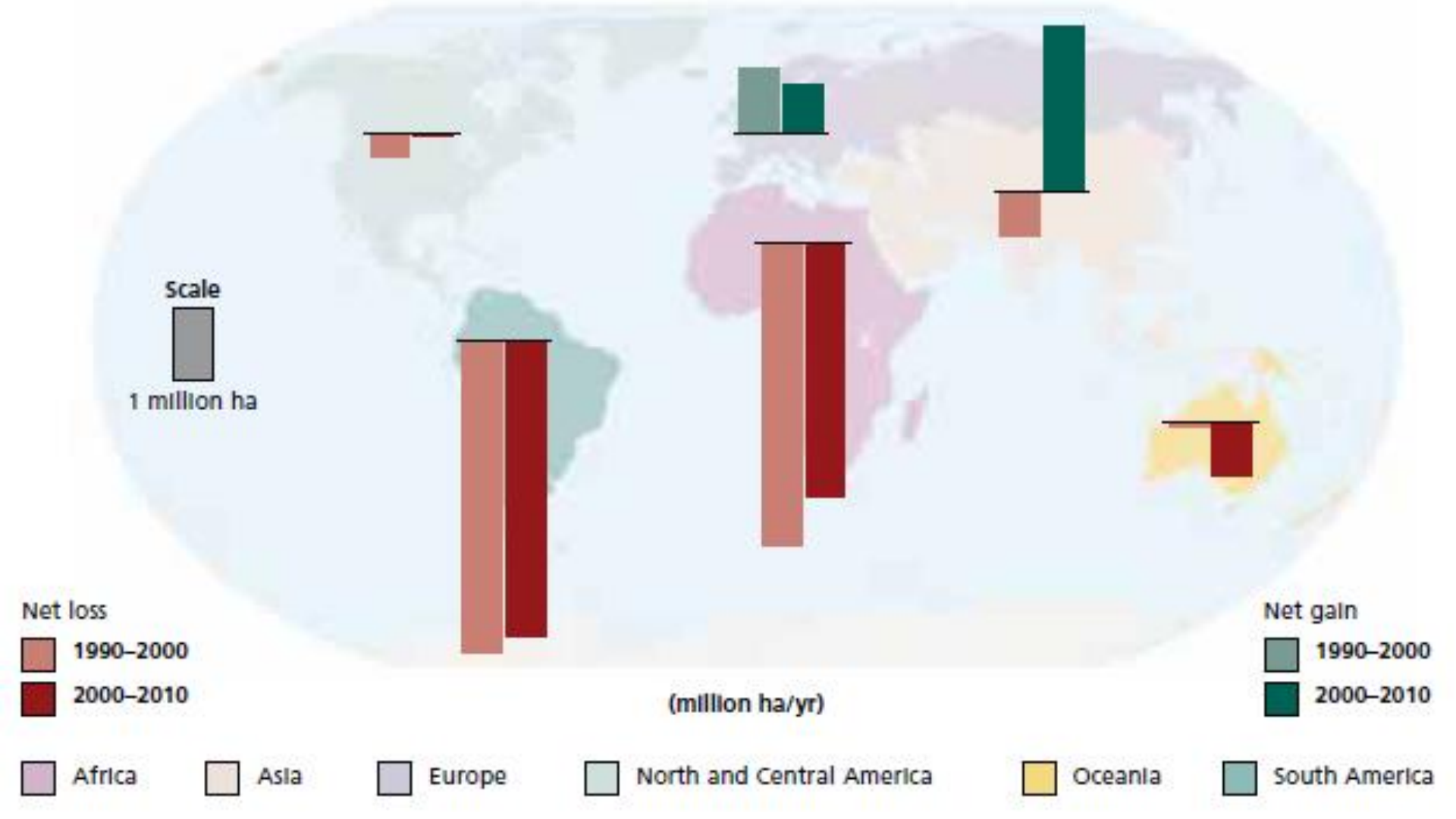
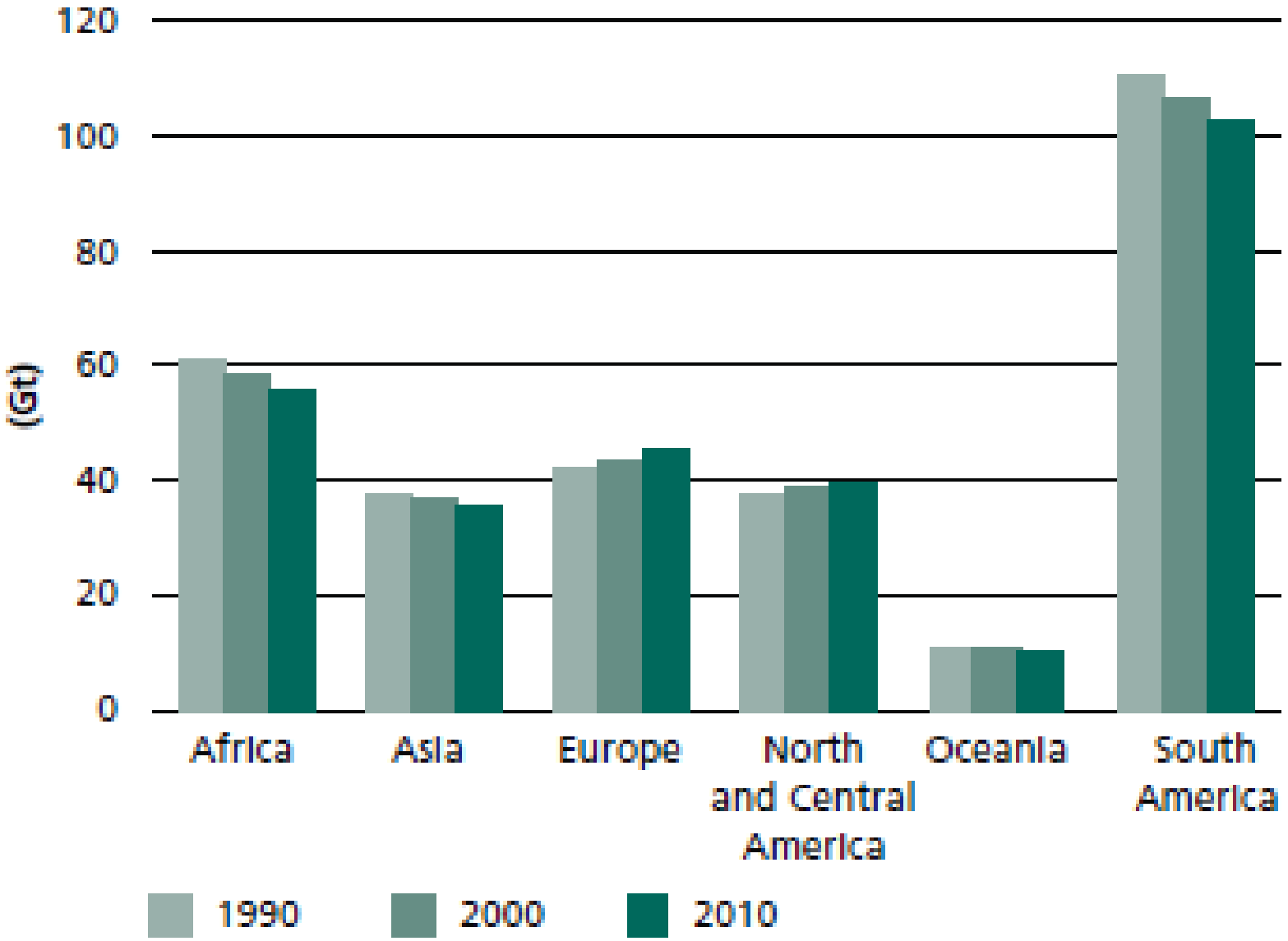


FIGURE 6

Trends in carbon stocks in forest biomass, 1990–2010



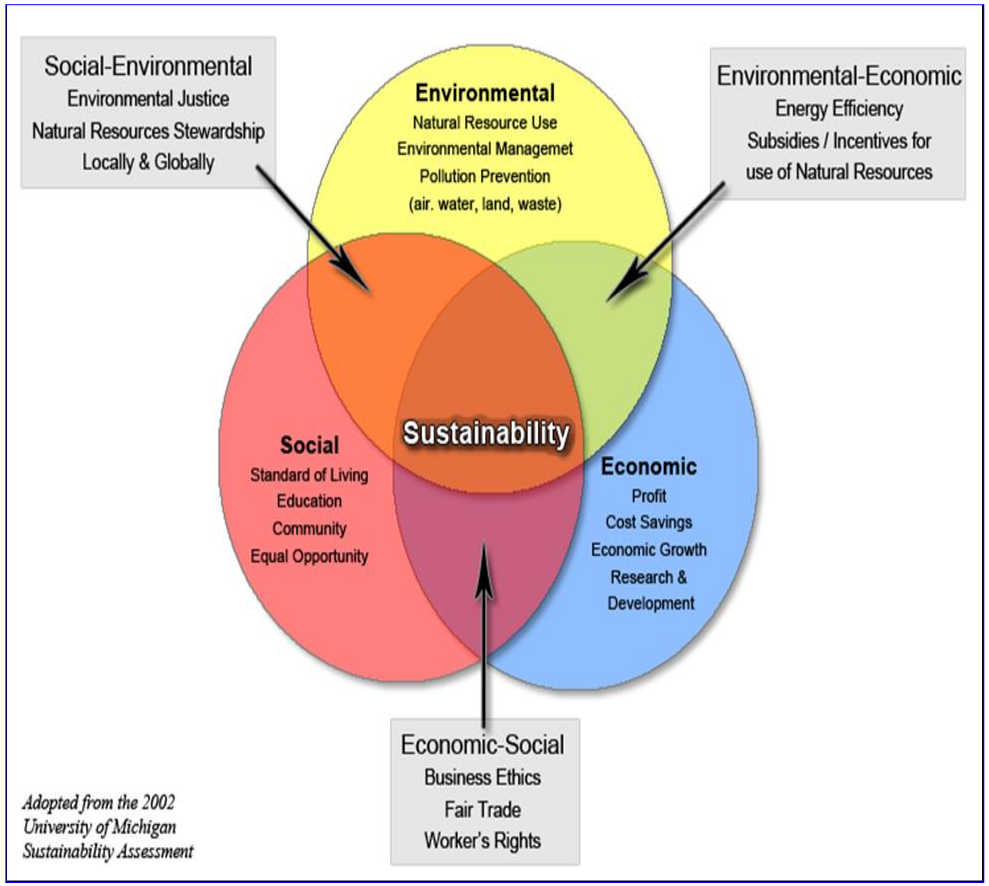
Complexities of global sustainable supply chain

Global brands strategically source raw materials from emerging markets for operating cost efficiencies

- *Indonesia, China, Vietnam, Brazil, Africa*

Global brands looking to establish a zero deforestation policy

- Brands are sourcing globally under intense public scrutiny and have responded with sustainable global sourcing policies
  - *McDonald's, Nutela, 3M, Disney, Unilever, Procter & Gamble, APP*
  - *Publishers - Environmental Book Council, Random House Penguin*
  - *Retailers – Walmart, Marks & Spencer, Loblaws*



Slide courtesy of Ian Lifshitz, APP

Sustainable Sourcing Options

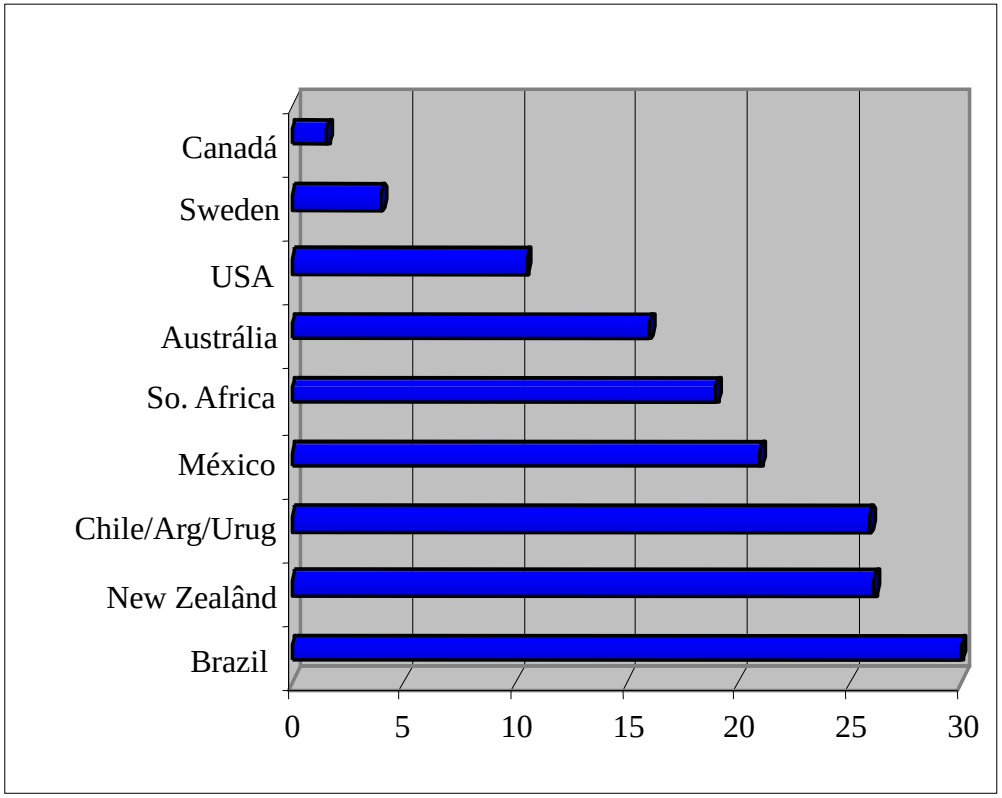
- **Certifications help ensure the public that products are sourced sustainably**
  - Guideline for suppliers to provide proof that manufacturers invest in sustainable production
  - Commitment from suppliers to economic and social development in the countries where materials are produced
  - Commitment to sustainable practices; 100% compliance with the laws of the raw materials' country of origin

- **Multiple types of certification**
  - Legality – e.g., Lacey Act compliance (ban of illegally sourced wood and wood products); EUTR (European timber regulation);
  - Sustainability/Environmental – e.g., PEFC, SFI, FSC for sustainable forest management; ISO (world standard for sustainable production)

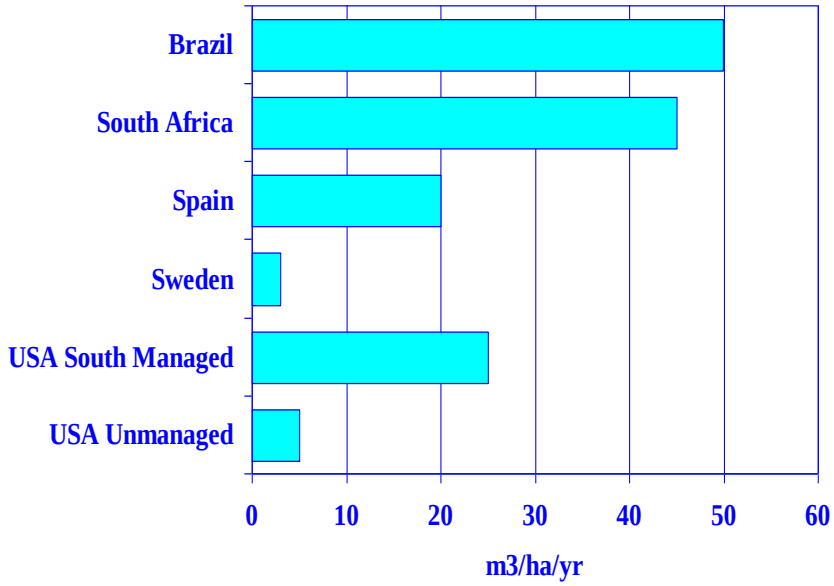
Slide courtesy of Ian Lifshitz, APP

Growth Rates (m3/ha/year)

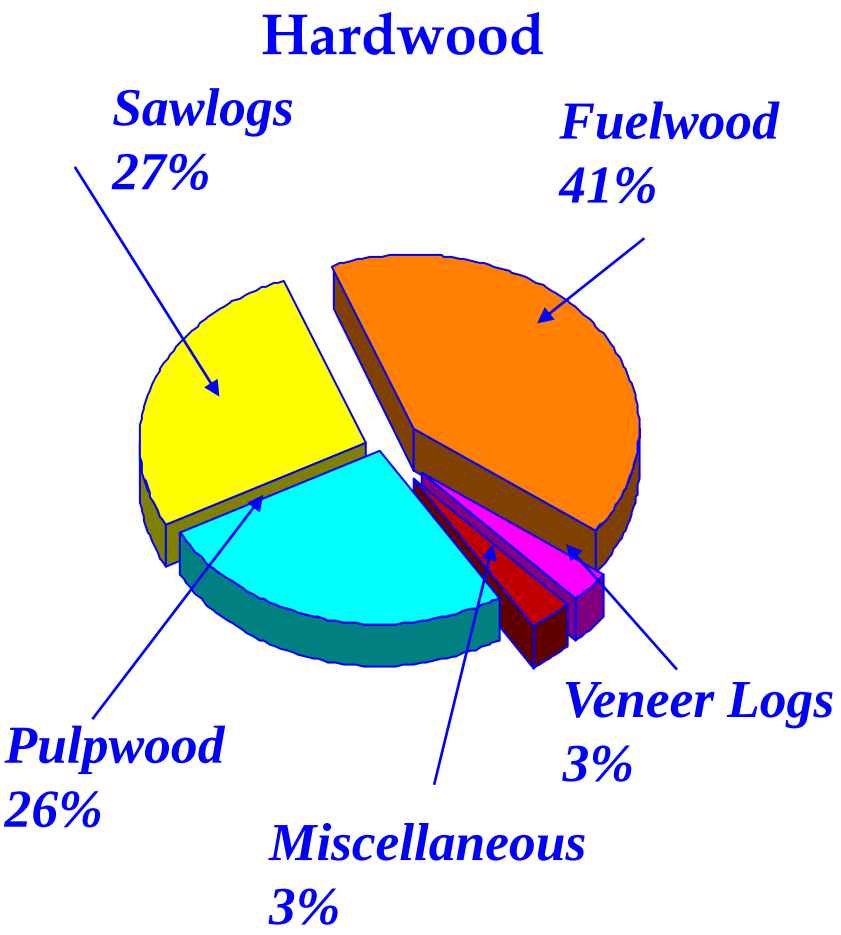
Softwood Growth Rates
Pine Plantations

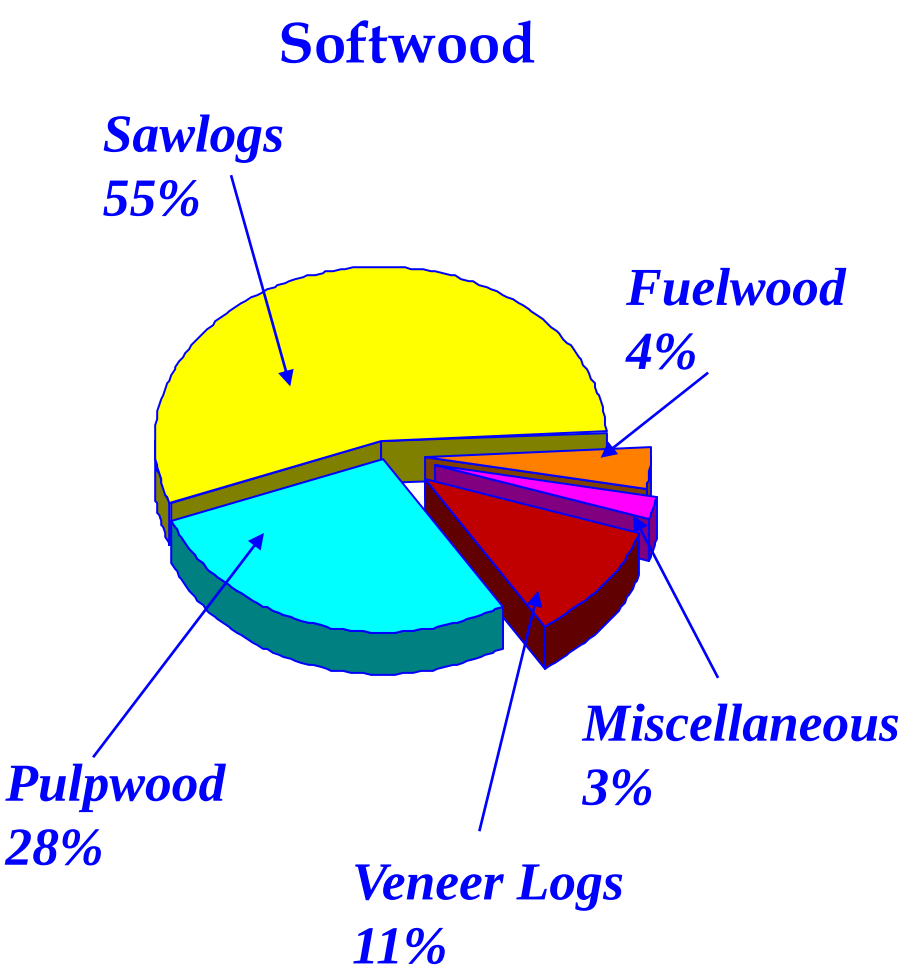


Hardwood Growth Rates



Industrial Wood Consumption





Generic Woodyard Flow Chart

All waste streams used for green energy

Chips

Roundwood

Wood Storage

Debarking

Bark to Hog Fuel Boiler

Chipping

Chip Storage

Undersize (pins + sawdust) to Hog Fuel Boiler

Screening

Over-Size

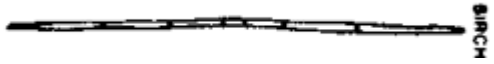
Rechipper

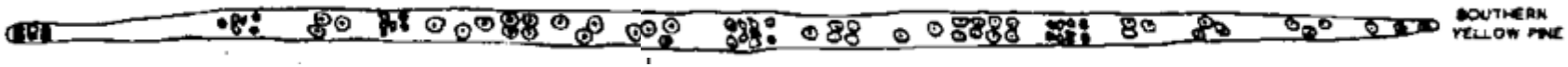
Chip Pile

Digesters

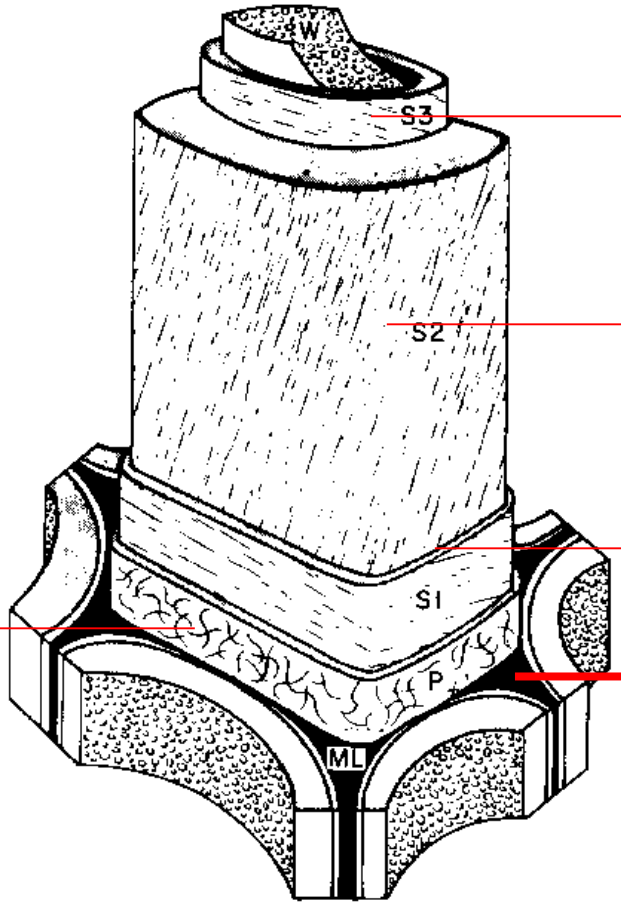
Softwood (left) and hardwood (right)

- *Softwood is long (4mm) and strong: used for paperboard that needs high strength*
- *Hardwood is short (1 mm) and fine: used for printing grades that need smoothness*





Fiber & Cell Wall



S3

S2

S1

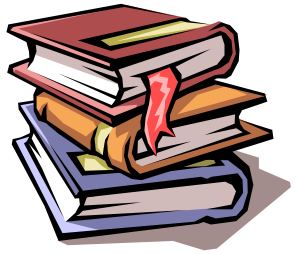
Secondary Wall (Cellulose/hemicellulose, white, 75%, makes good paper)

Primary Wall

Middle Lamella (concentrated lignin, glue, 25%, yellows, makes paper weak)

Releasing the fiber from the lignin (chemically or mechanically pulping) is the 1st step in making paper.

Section Summary

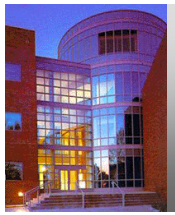


- There is a net reduction of forest lands, about 0.1% loss per year
- Significant losses in forest lands from sensitive areas that support wildlife diversity, while other areas have increases

- Wood comes into the mill as chips or logs

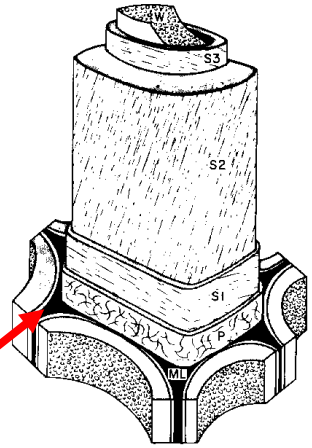
- Softwoods are long fibers, make strong paper
- Hardwoods are short fine fibers, make smooth paper for writing
- Wood contains cellulose, hemicellulose and lignin
- Lignin glues the cellulose based fibers together in wood

Questions?



3. Pulp and Paper Manufacturing

What is Pulping ?

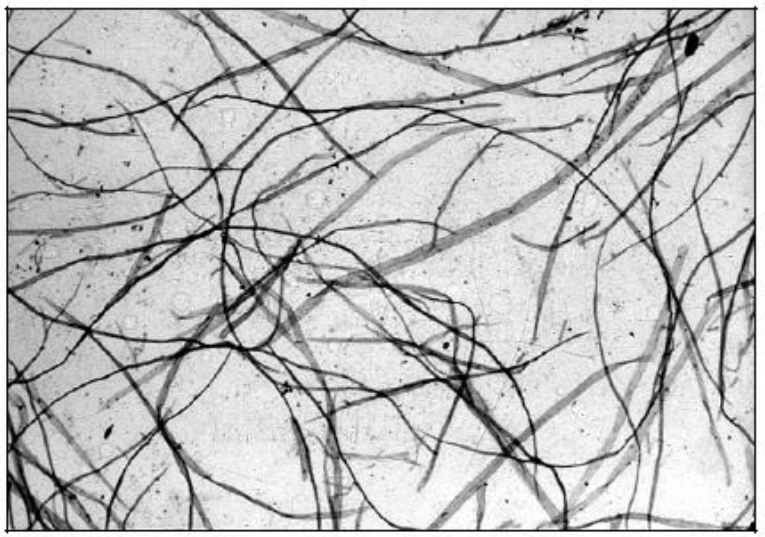


Middle Lamella Concentrated in lignin (glue)

The fibers have to be separated at the middle lamella (*mostly lignin*) without damaging the fibers

Pulping Methods

- Use chemicals that dissolve the lignin in the middle lamella so that the fibers can be separated easily
  - CHEMICAL PULPING



- Apply mechanical energy to cause the fiber to break away
  - MECHANICAL PULPING

Chemical Kraft Pulping

Key points: uses green energy, energy sufficient often, recycles chemicals and water

Logs

Debarking Drum

Chipper & Screens

Chips

Digester

White Liquor
Na_2S, NaOH

Pulp & Black Liquor

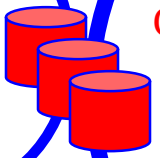
Wash Water

Lime Kiln

Lime

CaO

Lime Mud $CaCO_3$



Caustic Plant

Green Liquor
Na_2S, Na_2CO_3

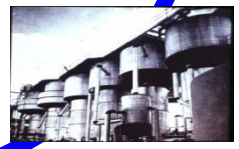
Washers

Pulp

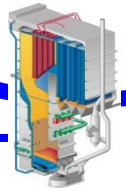
Screens & Cleaners

Weak Black Liquor

Evaporators



Recovery Boiler

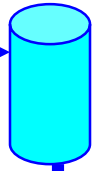


Strong Black Liquor

Power

Turbine Generator

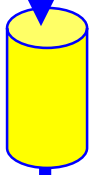
Steam



Brown Pulp Storage

Wash Water

Bleach Plant



Bleach Pulp Storage

To Paper Machine

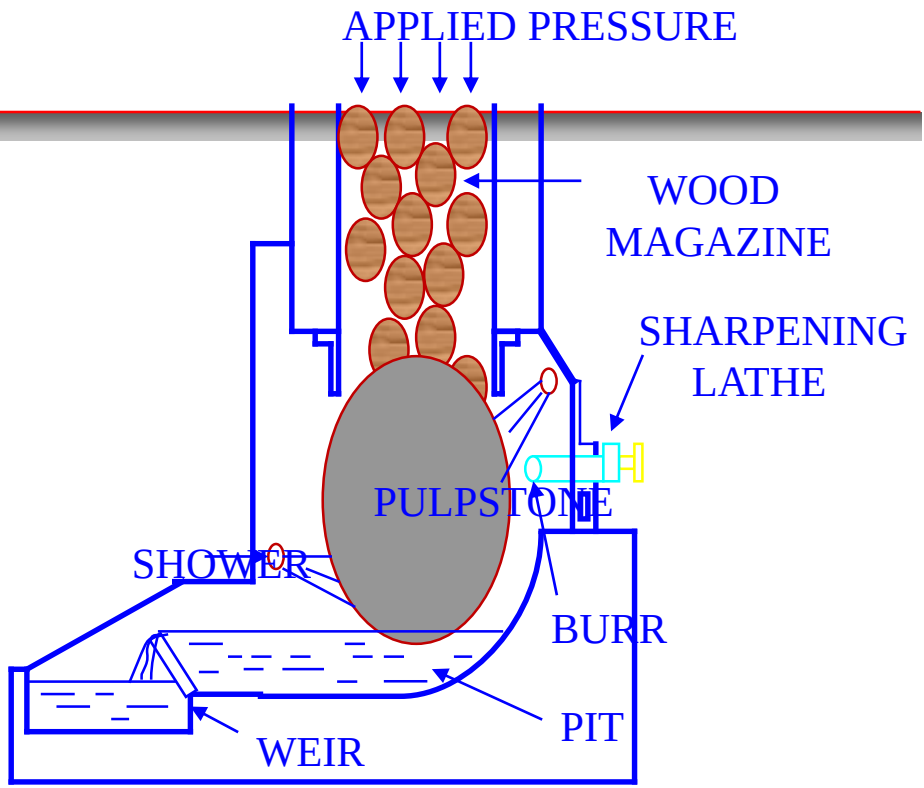
Bleaching of Chemical Pulps

- *After kraft pulping, some **lignin remains** making the pulp dark brown*
- ***Bleaching** with chlorine dioxide, alkali, and peroxide renders the pulp bright white*
- *About 20-30 years ago **elemental chlorine** was used, but its use has stopped due to **environmental concerns***
- *Currently, **chlorine dioxide** is used to bleach **97% of pulps**, this is called **ECF***
- ***Total chlorine bleaching** (**TCF**, no chlorine dioxide at all) is used as a specialty product*
- *No relevant environmental improvements have been documented for TCF over ECF*

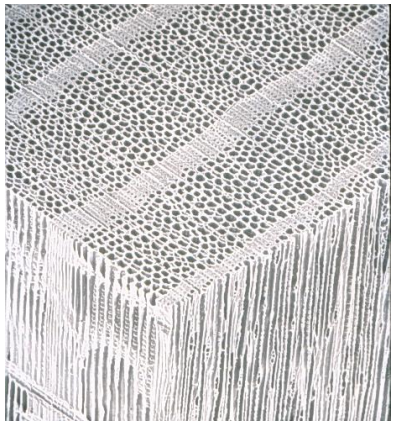
Mechanical Pulping

- Most of the constituents of wood retained
  - Results in high yield (90-95%)
- Composed of fiber bundles, fiber fragments, some whole fibers
- Weak sheet. Long fibers need to be mixed.
- High opacity and good printing product

- High lignin content makes it discolor easily
- High energy usage



How is paper made?

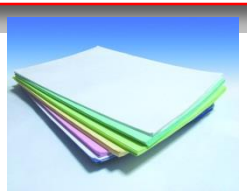


Wood contains papermaking fibers glued by lignin in a matrix.

Chemical (kraft) pulping (circa 45% yield)

Unbleached kraft pulp (corrugated boxes)

Bleaching



Bleached Pulp (zero lignin, permanent, printing grades)

Mechanical Pulping (90+ % yield)

Mechanical Pulp (lignin containing, yellows with age) (newsprint, magazines)

North American Pulp Production

- Mechanical Pulping = 21% of production
- Chemical Pulping = 72% of production
- Semichemical = 5% of production

	2010	***2011***	***%***
Chemical	*51,986*	*52,470*	*75*
Mechanical	*12,586*	*12,001*	*17*
Semichemical	*3,282*	*3,577*	*5*
Dissolving	*1,514*	*1,952*	*3*
Total	*69,368*	*70,001*	*100*

Questions?

Papermaking

- The process of making a slurry of fibers in water into a consolidated sheet of paper
- We use **water** to distribute the fibers randomly in a network
- Removing the water gives the sheet strength
- Cellulose fibers use hydrogen bonding to develop strength in paper, no glue is needed
- *Did you know paper is stronger than steel on a weight basis?*
- This makes paper recyclable, add water, remove the bonds

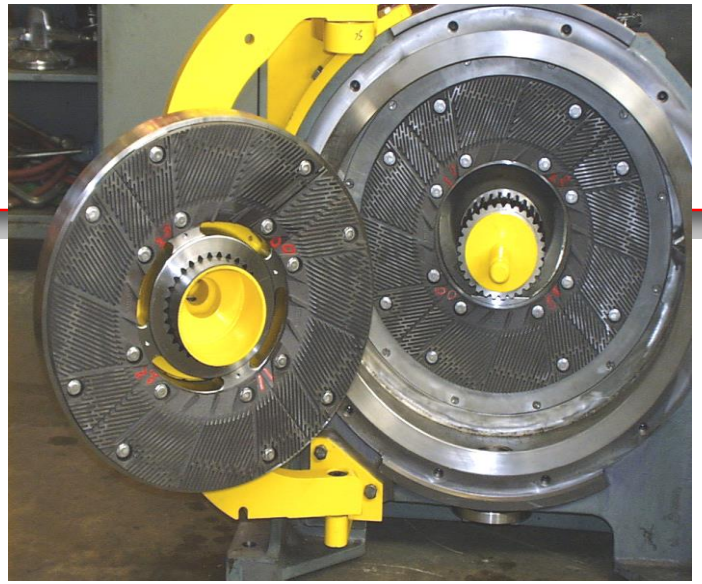
Paper Machine Operations

- Dilute fibers in water in a headbox (0.5%)
- Deliver the fibers onto a moving wire
- Remove water
  - Gravity; Vacuum; Pressing; Heat drying
- Collect on a reel

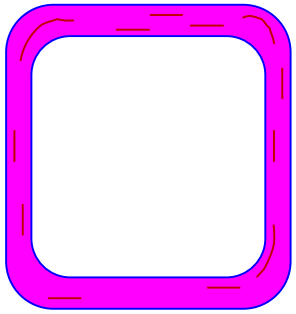
Typical Paper Making Furnishes

	Copy Paper (Uncoated Free Sheet)	Linerboard (Top Liner)	Premium Bath Tissue	Market Pulp	Fluff Pulp
Fibrous Component	20% softwood (for strength) 80% hardwood (for smoothness) Bleached	100% virgin softwood unbleached OR 100% recycled (OCC)	20% northern softwood kraft (for strength) 80% eucalyptus (for softness)	100 % hardwood OR 100% softwood	100% southern softwood
Additives	- Retention aid (starch or CPAM) - Fillers (clay and/or calcium carbonate) - Sizing (ASA or AKD) - Wet strength agent (starch) - Alum????	- Retention aid (starch or CPAM) - Sizing (rosin, for acid papermaking) - Alum (to set rosin on fiber) - Dry strength agent (starch) - Wet strength agent?	- Retention aid (starch or CPAM) - Wet strength agent (GPAM for short-term strength) - Debonder for softness (quaternary amine)	Only runnability aids	- Debonder (to reduce fiberization energy for customer) - Runnability aids
Refining	Moderate to High	High	Very low (“tickle” refining)	None	None
Basis Weight	50 – 100 g/m2	125 – 430 g/m2	12-20 g/m2	400 – 800 g/m2	685 – 765 g/m2

Refining

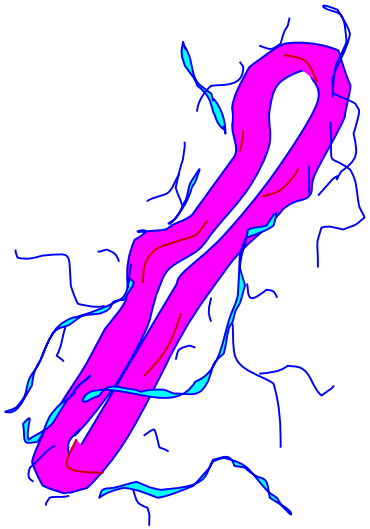


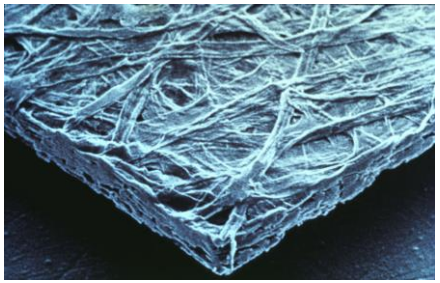
- **Refining** is a physical treatment performed on pulp fibers to improve their papermaking characteristics
- It is essential to production of **strong, smooth, useful** paper
- **Electricity intensive**: 40-400 kWhr/ton
  - Lightbulb is 0.06 kWhr



Native shape

Refining



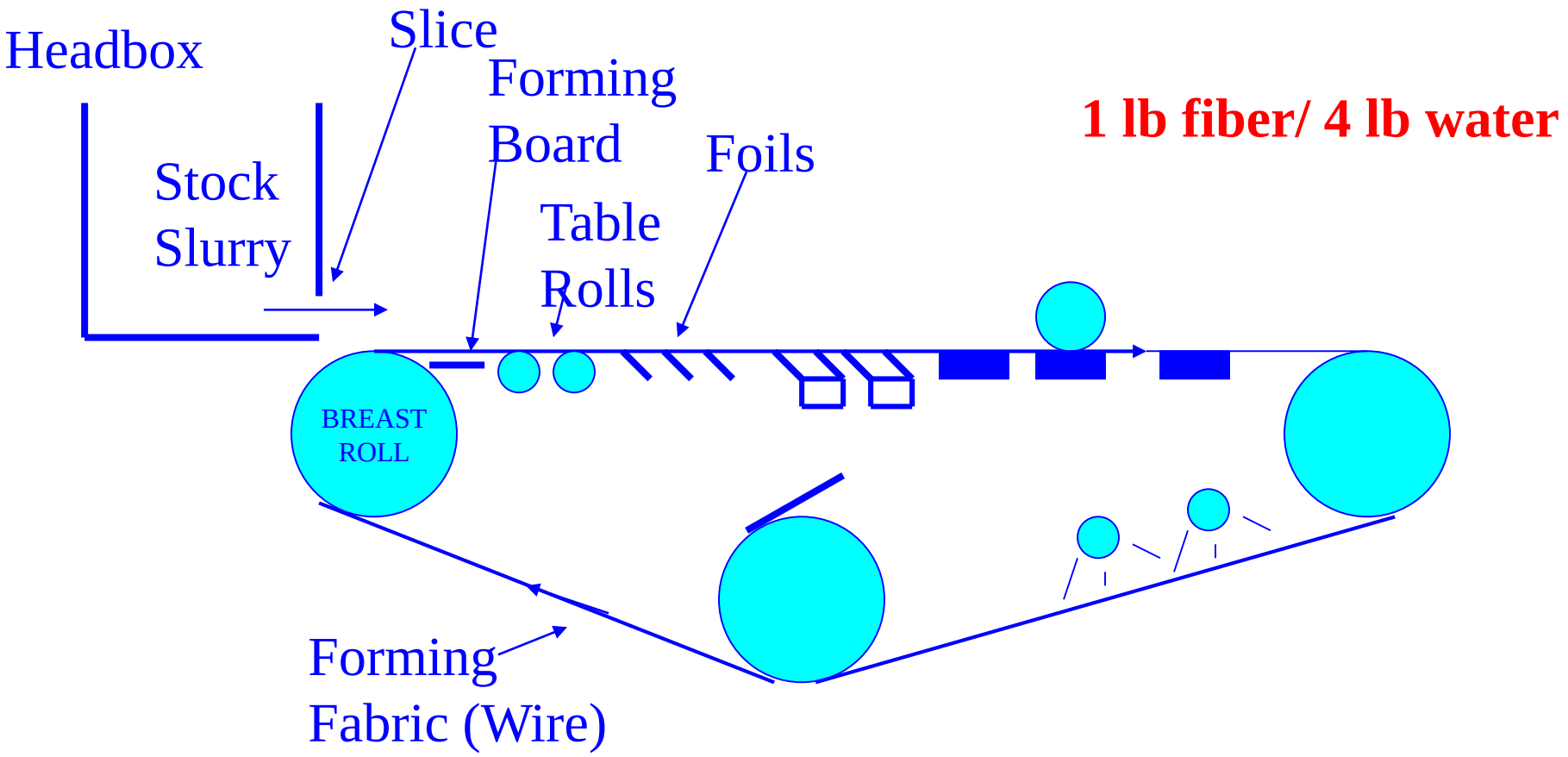


M. Hubbe, online encyclopedia of paper: http://www4.ncsu.edu/~hubbe/

Elements of the Gravity Section

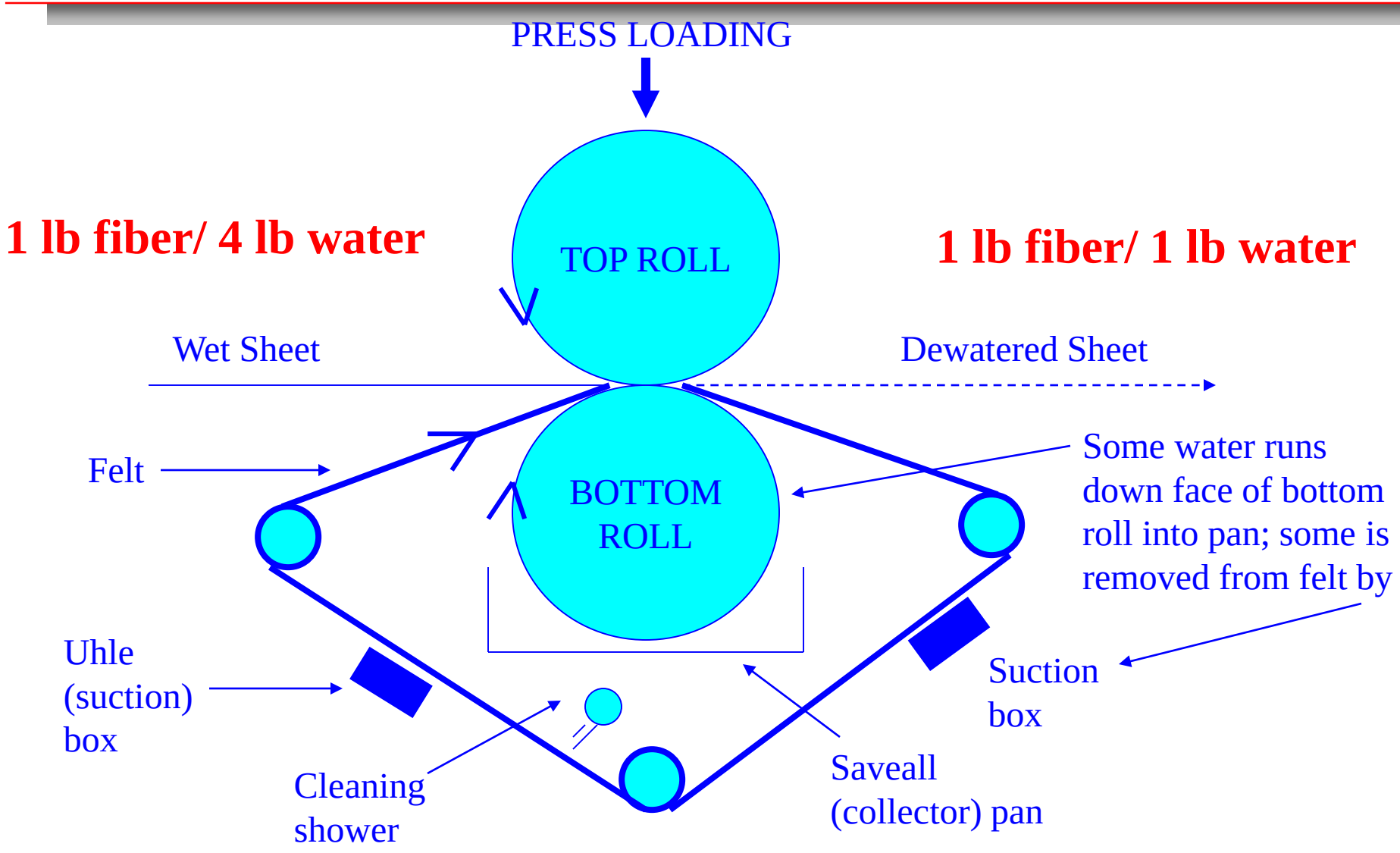
The paper can travel at speeds of 80 miles per hr!! Paper Breaks are not fun.
If this machine makes 1000 tons per day, it drains about 200,000 tons per day of water!

1 lb fiber/ 200 lb water



1 lb fiber/ 4 lb water

Presses to Remove Water



Paper Drying Drums

1 lb fiber/ 1 lb water

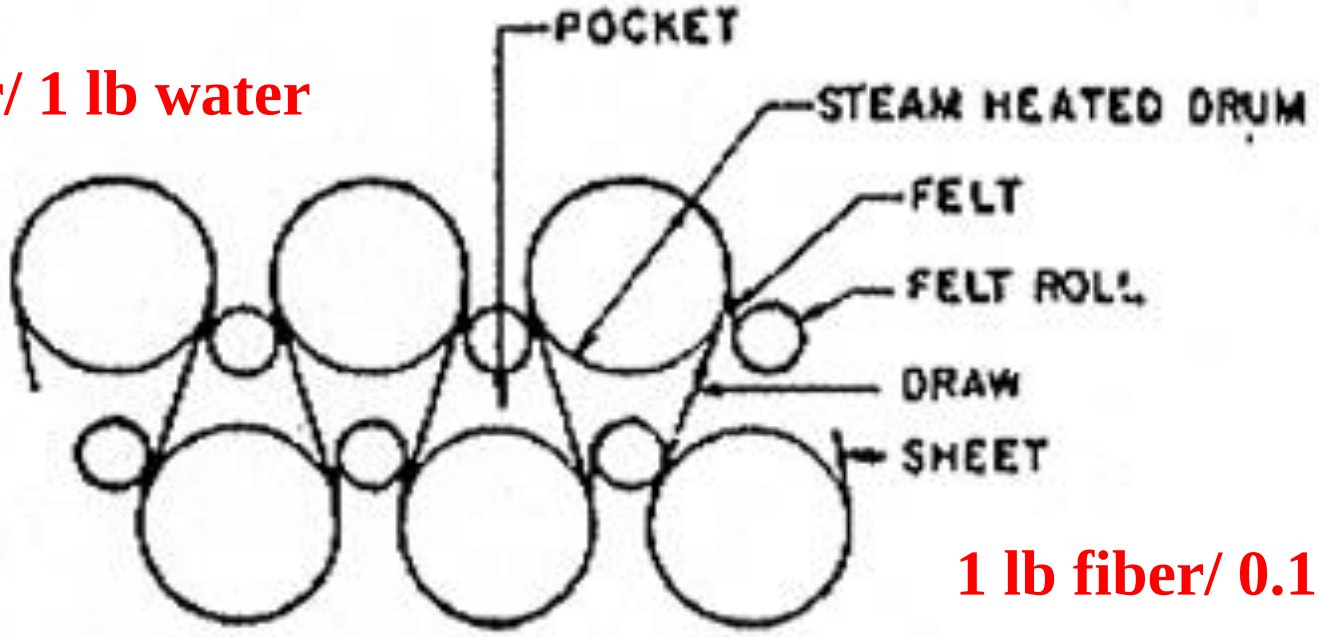
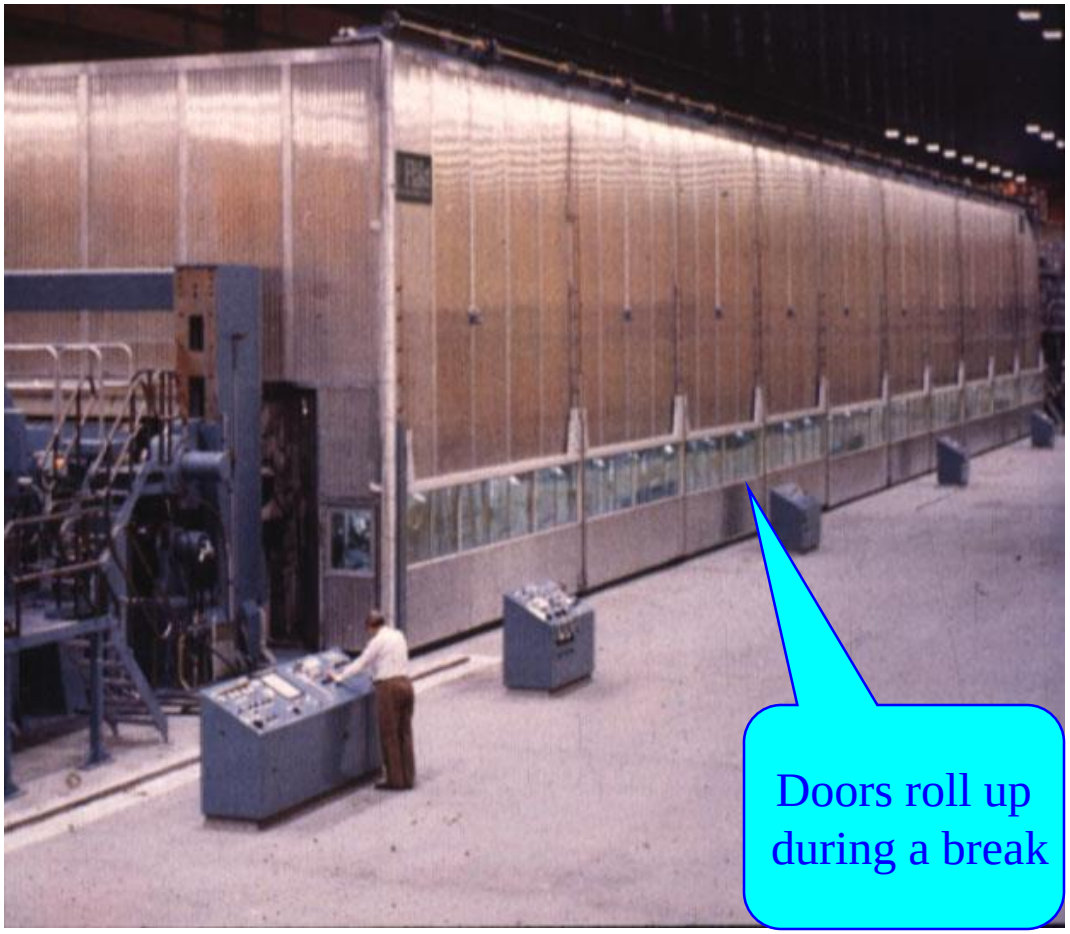


Fig. 17-7. The drying configuration.

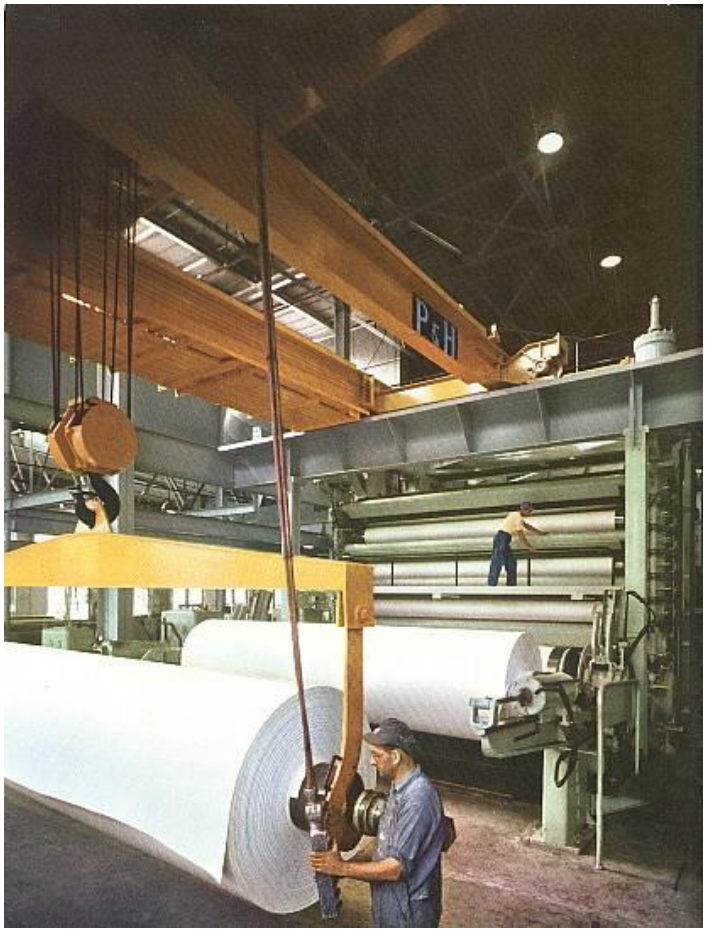
1 lb fiber/ 0.1 lb water

Paper machines are as long as a football field, see person on left.

Enclosed dryer hood



Jumbo Rolls on Reel

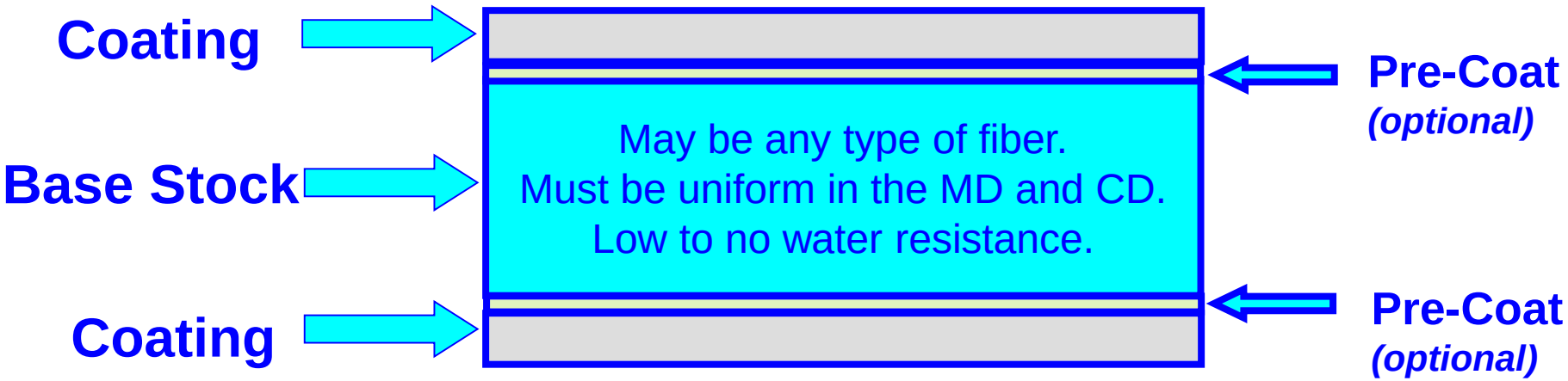


Converting Operations

- Sheeting of paper
- Creation of boxes
  - *corrugated*
- Coating
- Tissue making
- Others

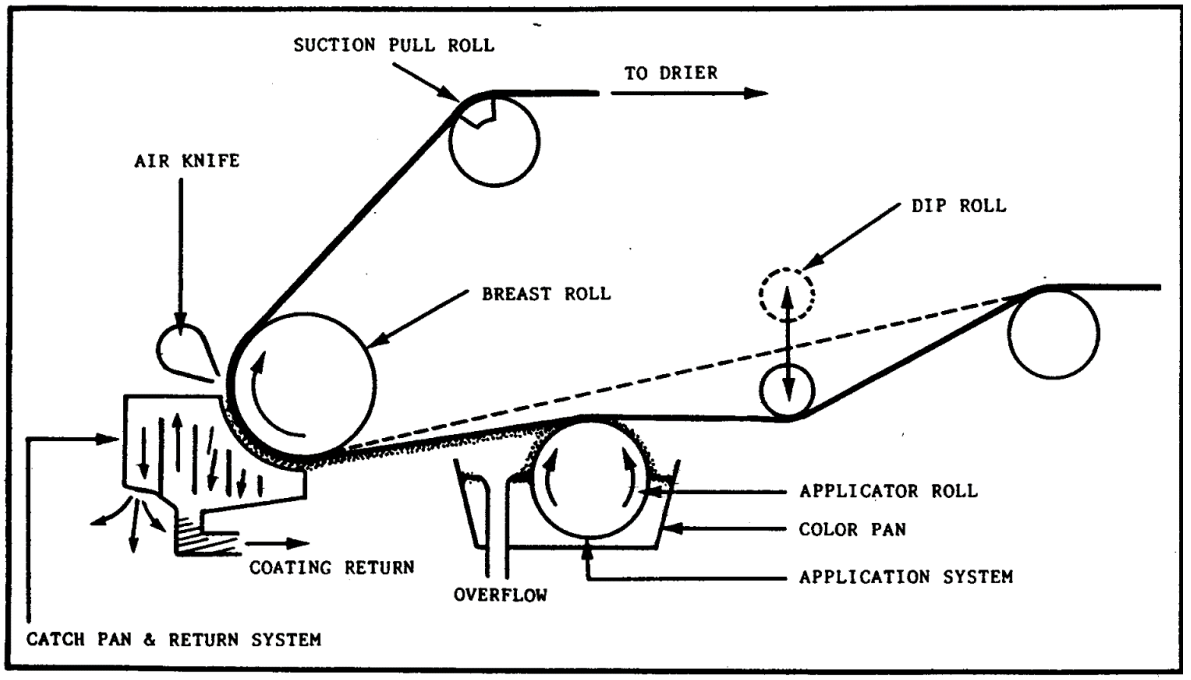
What is coating?

- It is often said that papermakers do not sell paper, but sell a surface. By coating the paper we can dramatically improve the smoothness, gloss, brightness, and opacity. This creates a surface that is desirable to many customers.



Coating Formulation

- The coating may form up to 30% of the total weight of paper.
- The coating typically consists of:
  - Water
  - Pigments
  - Binders
  - Additives
- Typically the paper is passed through a reservoir of the coating and then doctored by blade, air or rod to a uniform thickness



Section Summary

Pulping to liberate fibers

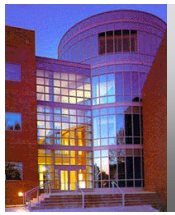
Need certain types of fibers for certain products.

Papermaking is a huge dewatering process.

Drying is a huge consumer of energy.

Converting operations to make usable products, add value.

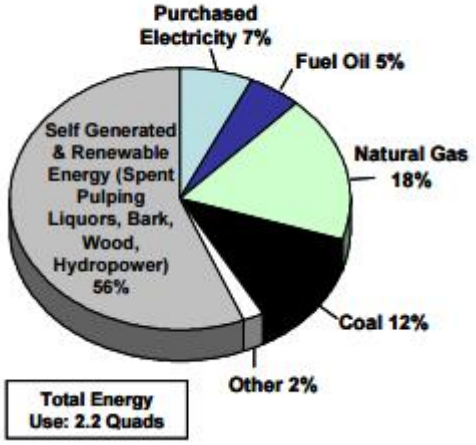
Questions?



4. Environmental Impacts

Natural Resources Consumed

- **Wood**
  - *Mechanical pulp uses ~2 tons of wet wood per ton of paper*
  - *Chemical pulp uses ~4 tons of wet wood per tone of paper*
    - *Mass loss of woody material used for green energy (DOE Data below)*
- **Water**
  - *Use ~40-100 tons of water per ton of paper produced*

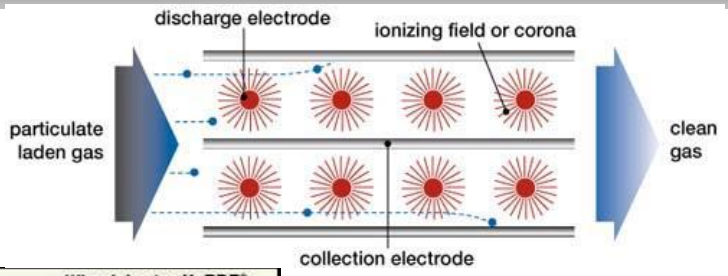


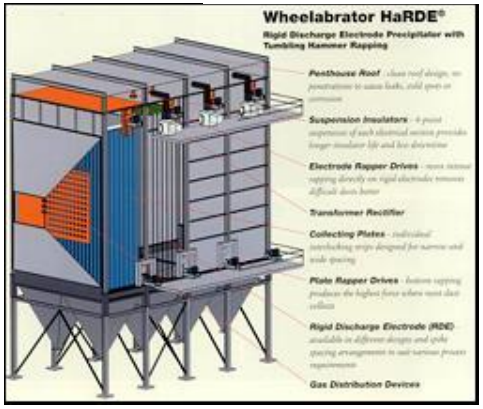
Wastes Generated

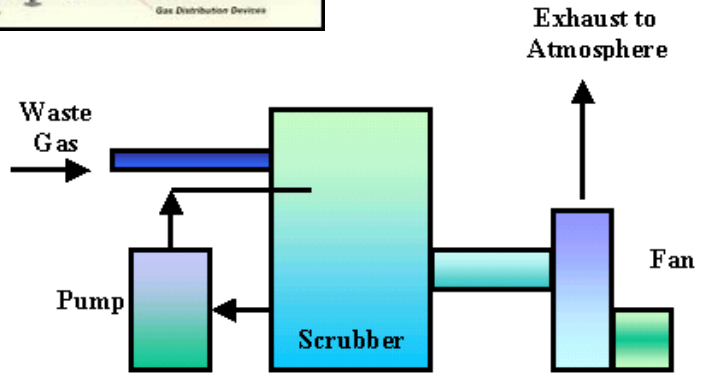
- Air emissions
- Water emissions
- Solid waste

Air Emissions

- **Particulates**
  - Recovery boilers
    - *soda fumes (Na_2SO_4, Na_2CO_3, NaCl)*
  - Coal and hog fuel boilers
    - *fly ash (ash, char)*
  - Lime kilns
    - *lime dust ($CaCO_3$)*
- **Control**
  - Fabric filtration
  - Electrostatic precipitation
  - Wet scrubbing







Scrubbing the Gas

Air Emissions

- **Gaseous emissions**
  - Nitrogen oxides
    - *all high temperature combustion processes*
  - Reduced sulfur gases (TRS): causes odor
    - *all kraft pulping and recovery operations*
    - *hydrogen sulfide (1ppb), methyl mercaptan (1ppb), dimethyl sulfide (10ppb), dimethyl disulfide (10ppb)*
    - *ppb = part per billion, one drop of ink in a gasoline tanker truck*
    - *ppb = 1 / 1,000,000,000*
  - Volatile organic compounds (VOC)
    - *Non-condensable gases from digester, liquor evaporation, bleaching*
    - *alcohols, terpenes, phenols, chloroform*

- **Control: Collection of the gases**
  - Thermal incineration: lime kiln, boilers, incinerators
  - Wet scrubbing
  - Catalytic combustion
  - Adsorption

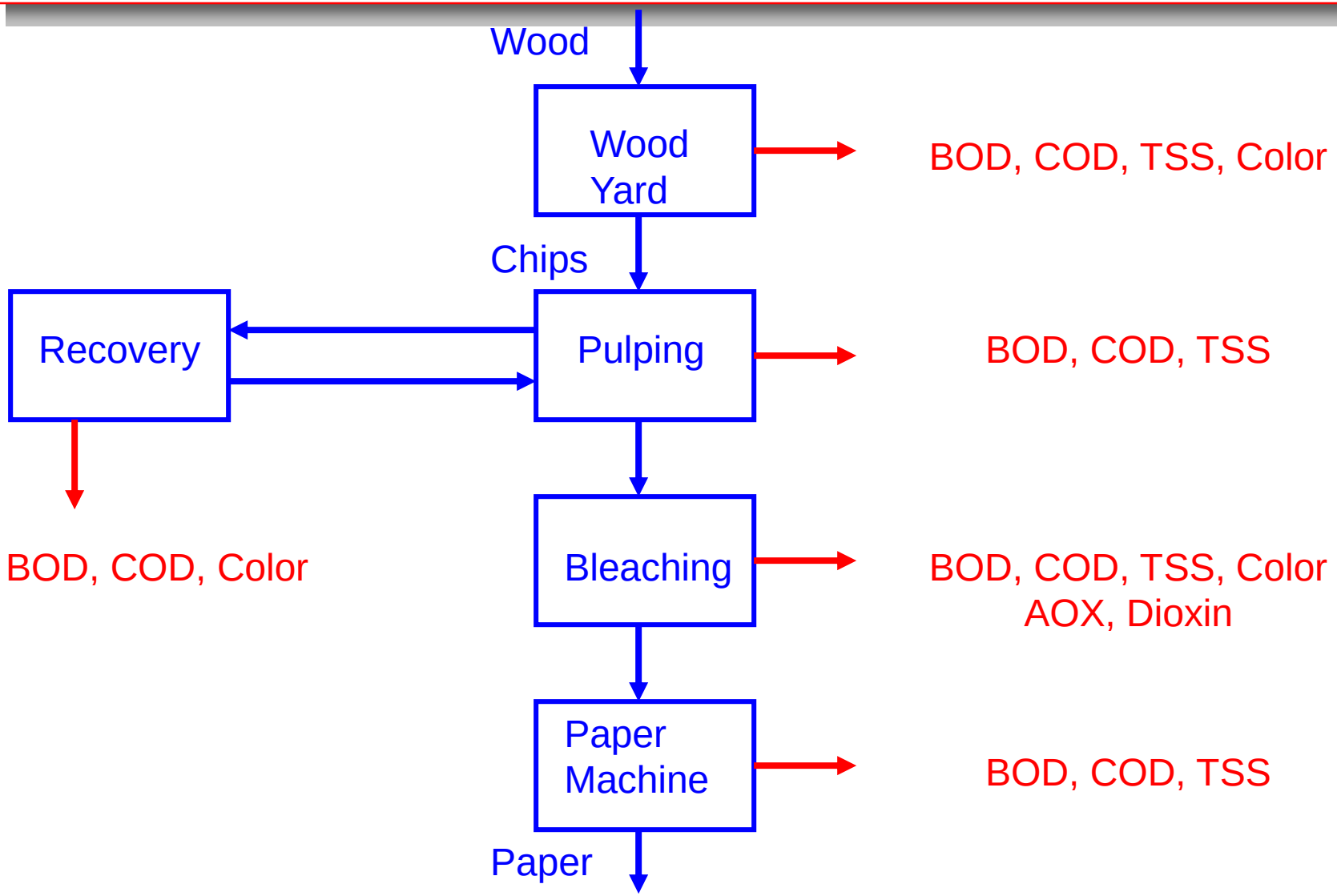
Kraft Mill Example: EPA DMR & TRI Data

AIR					Mt Emissions	
Program	Pollutant	Units/year	2013(mt/hr)		Per mt Raw Mat	Per admt SBSK
GHG	Methane	MTCO2e	32,478.75	3.87E+00	2.62E-02	7.36E-02
GHG	Carbon dioxide	MTCO2e	1,998,394.80	**2.38E+02**	1.61E+00	4.53E+00
GHG	Nitrous oxide	MTCO2e	9,179.89	1.09E+00	7.40E-03	2.08E-02
TRI	Ammonia	Pounds	152,322.00	8.23E-03	5.57E-05	1.57E-04
TRI	Formaldehyde	Pounds	5,227.00	2.82E-04	1.91E-06	5.37E-06
TRI	Chlorine	Pounds	1,985.00	1.07E-04	7.26E-07	2.04E-06
TRI	Lead compounds	Pounds	166.4	8.99E-06	6.09E-08	1.71E-07
TRI	Phenol	Pounds	5,620.00	3.04E-04	2.06E-06	5.78E-06
TRI	Vanadium compounds	Pounds	10	5.40E-07	3.66E-09	1.03E-08
TRI	Zinc compounds	Pounds	895	4.83E-05	3.27E-07	9.20E-07
TRI	Hydrochloric acid	Pounds	59,712.00	3.23E-03	2.18E-05	6.14E-05
TRI	Manganese compounds	Pounds	506	2.73E-05	1.85E-07	5.20E-07
TRI	Polycyclic aromatic compounds -- TRI	Pounds	207.5	1.12E-05	7.59E-08	2.13E-07
TRI	Barium compounds -- TRI	Pounds	494	2.67E-05	1.81E-07	5.08E-07
TRI	Hydrogen sulfide	Pounds	77,574.00	4.19E-03	2.84E-05	7.98E-05
TRI	Mercury compounds	Pounds	14	7.56E-07	5.12E-09	1.44E-08
TRI	Acetaldehyde	Pounds	29,056.00	1.57E-03	1.06E-05	2.99E-05
TRI	Methanol	Pounds	541,031.00	2.92E-02	1.98E-04	5.56E-04
TRI	Formic acid	Pounds	195	1.05E-05	7.13E-08	2.01E-07
TRI	Chlorine dioxide	Pounds	5	2.70E-07	1.83E-09	5.14E-09
	SUM Emissions (less CO2e)			**4.73E-02**	**3.20E-04**	**9.00E-04**

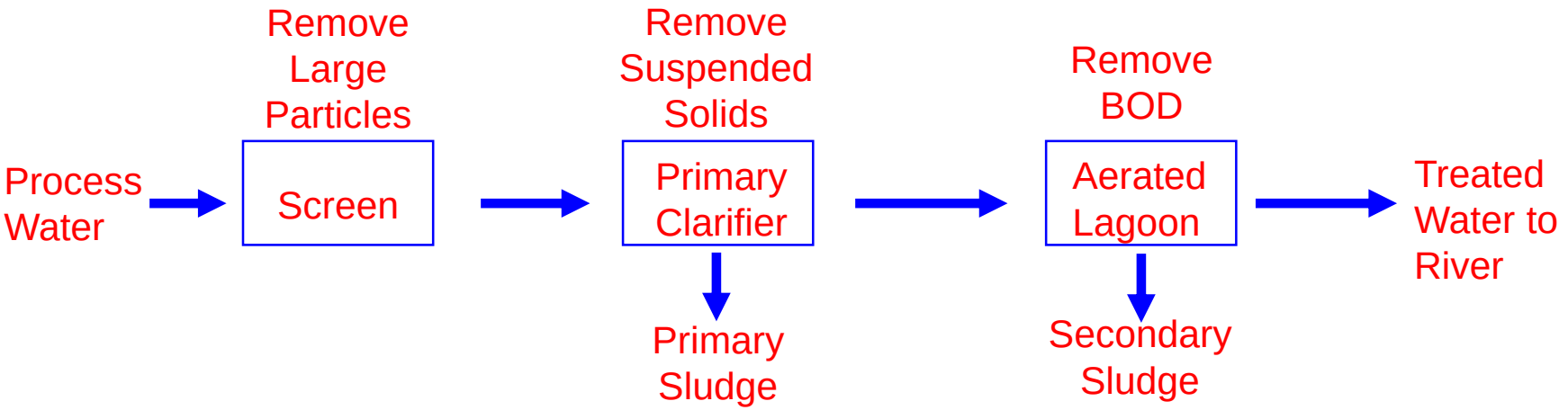
Water Pollution

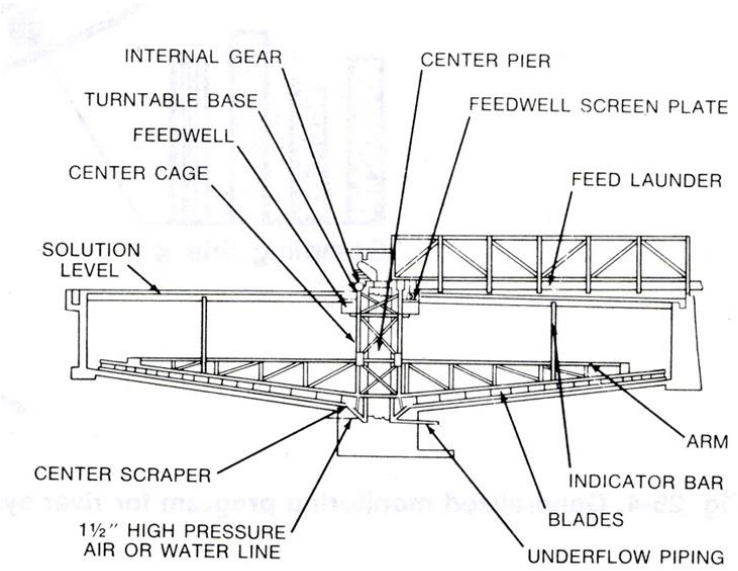
- Any change in the condition of water which is detrimental to some beneficial use
  - Effluent solids
    - *Total suspended solids*
  - Oxygen demand – Organic compounds from a mill can deplete oxygen in the water needed for living organisms --- COD or BOD
  - Chlorinated compounds
    - *Absorbable organic halides (AOX)*
    - *Chlorinated dioxin and furans*
  - Color

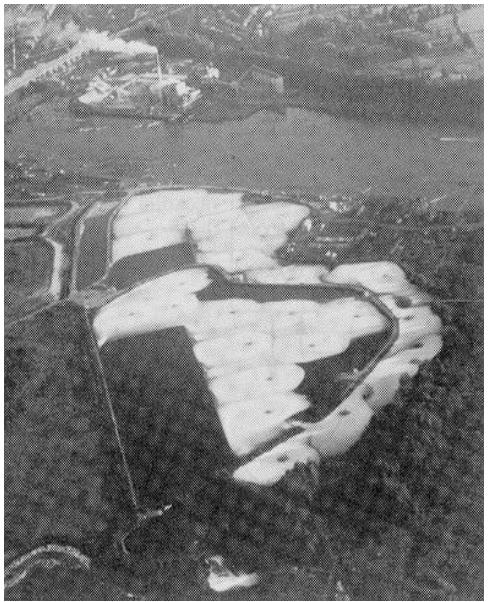
Origin of Waste Load



External Treatment







Kraft Mill Example: EPA DMR & TRI Data

WATER

Discharges to Chemical Groups by Pounds (lbs)

Chemical Group 2013 20132013 Total

	DMR	TRI	SUM	Mt Emissions		
	(lbs/yr)	(lbs/yr)	(lbs/yr)	(mt/hr)	Per mt Raw Mat	Per admt SBSK
ACETALDEHYDE		5,723	5,723	3.09E-04	2.09E-06	5.88E-06
AMMONIA	134,919	2,765	137,684	7.44E-03	5.04E-05	1.42E-04
BARIUM AND BARIUM COMPOUNDS		10,064	10,064	5.44E-04	3.68E-06	1.03E-05
BOD, 5-day, 20 deg. C	1,383,101		1,383,101	7.47E-02	5.06E-04	1.42E-03
CATECHOL		84	84	4.54E-06	3.07E-08	8.64E-08
FORMALDEHYDE		2,603	2,603	1.41E-04	9.52E-07	2.68E-06
FORMIC ACID		277	277	1.50E-05	1.01E-07	2.85E-07
Halogens, adsorbable organic	154,396		154,396	8.34E-03	5.65E-05	1.59E-04
HYDROGEN SULFIDE		409	409	2.21E-05	1.50E-07	4.21E-07
LEAD AND LEAD COMPOUNDS		137	137	7.40E-06	5.01E-08	1.41E-07
MANGANESE AND MANGANESE COMPOUNDS		43,752	43,752	2.36E-03	1.60E-05	4.50E-05
MERCURY AND MERCURY COMPOUNDS		3	3	1.62E-07	1.10E-09	3.08E-09
METHANOL		13,892	13,892	7.50E-04	5.08E-06	1.43E-05
NITRATE COMPOUNDS		17,910	17,910	9.67E-04	6.55E-06	1.84E-05
Nitrogen	348,613		348,613	1.88E-02	1.28E-04	3.58E-04
PHENOL		1	1	5.40E-08	3.66E-10	1.03E-09
Phosphorus	53,830		53,830	2.91E-03	1.97E-05	5.54E-05
Solids, total suspended	1,176,438		1,176,438	6.35E-02	4.30E-04	1.21E-03
VANADIUM AND VANADIUM COMPOUNDS		853	853	4.61E-05	3.12E-07	8.77E-07
ZINC AND ZINC COMPOUNDS		7,761	7,761	4.19E-04	2.84E-06	7.98E-06
SUM Emissions				**1.81E-01**	**1.23E-03**	**3.45E-03**

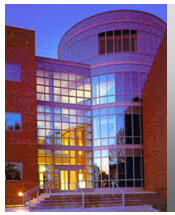
Solid Waste

- Generated from the removal of suspended solids from water treatment, from pulp cleaning rejects, from combustion ash, and from other rejects in the mill
- Typically is around 3-5% for a virgin mill and can be from 2-50% of incoming material for a recycled mill
- Sludges from water treatment dominate total flow, typically 50% water and a lot of organic material
- Currently a lot of research going on to find better ways to utilize

Section Summary

- Sources of pollution
  - Air - particulates, reduced sulfur gases, volatile organic compounds (VOC) , less than 1 kg per ton product
  - Water - suspended solids, oxygen demanding substances (BOD, COD), organic halide compounds (AOX), about 3 kg/ton product
  - Solid waste

Questions?



5. Paper Recycling

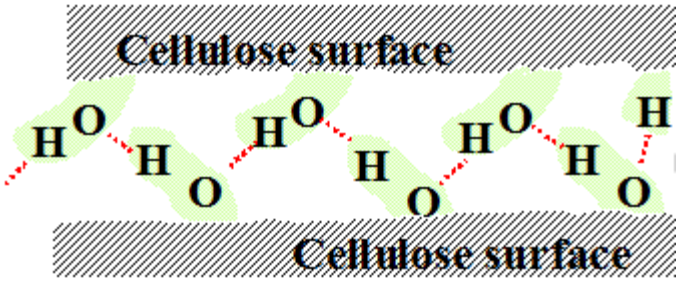
Why is paper recyclable?

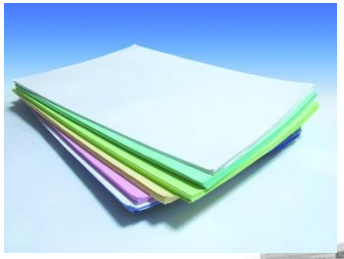
Paper is a random web of wood fibers that are bonded mainly with hydrogen bonding.

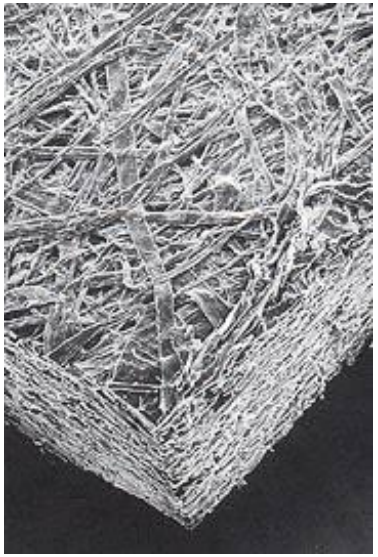
Hydrogen bonds are reversible, they are weakened when paper is put into water.

When wetted and mechanically agitated, paper falls apart into individual fibers.

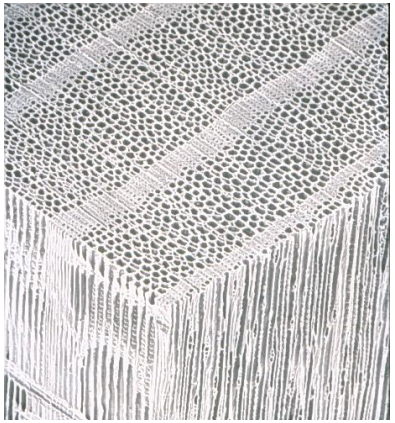
This is the basis of paper recycling.







How is paper made?



Wood contains papermaking fibers.

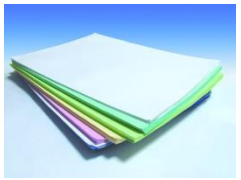
But lignin, a natural adhesive in wood, makes the fibers hard.

The fibers must be liberated from the wood by either chemical or mechanical actions.

Chemical (kraft) pulping (circa 45% yield)

Unbleached kraft pulp (corrugated boxes)

Bleaching



Bleached Pulp (zero lignin, permanent, printing grades)

Mechanical Pulping (90+ % yield)

Mechanical Pulp (lignin containing, yellows with age) (newsprint, magazines)

Major Recycling Systems

Categorize by the products they produce:

Unbleached Kraft Pulp, Packaging Materials (like corrugated boxes)

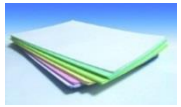
- *Typically, OCC (old corrugated containers) materials are recycled back into linerboard, medium, tube stock, and solid board products*

Newsprint (mechanical pulps)

- *Old newspapers (ONP) and magazines (OMP) are converted into newsprint*

Tissue (varied compositions of input paper)

- *Bleached printing and writing wastes are converted into tissue*



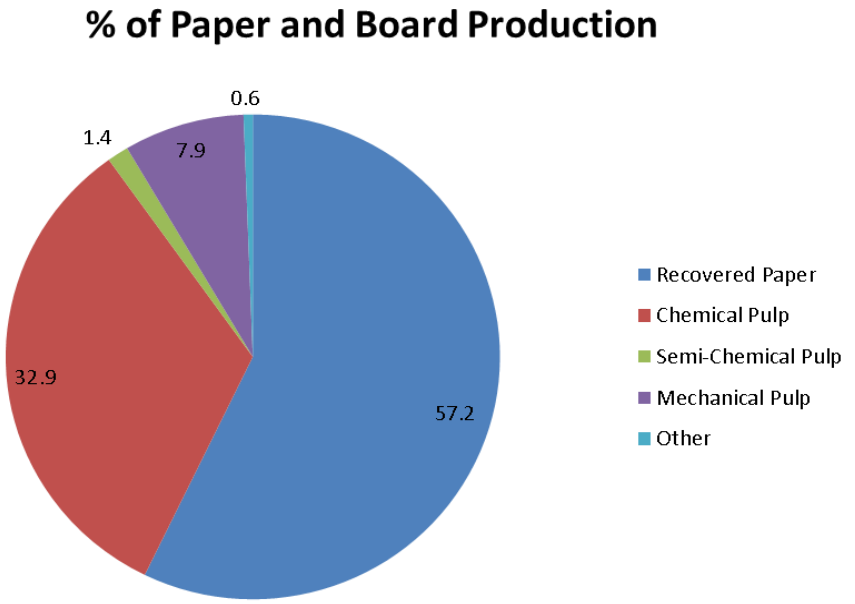
Printing and Writing Materials (bleached Kraft pulps)

- *Bleached printing and writing wastes are converted into pulp for application in new printing and writing grades*

Source: RISI

World Paper Production 2011

(Total Production = 400 million metric tons)

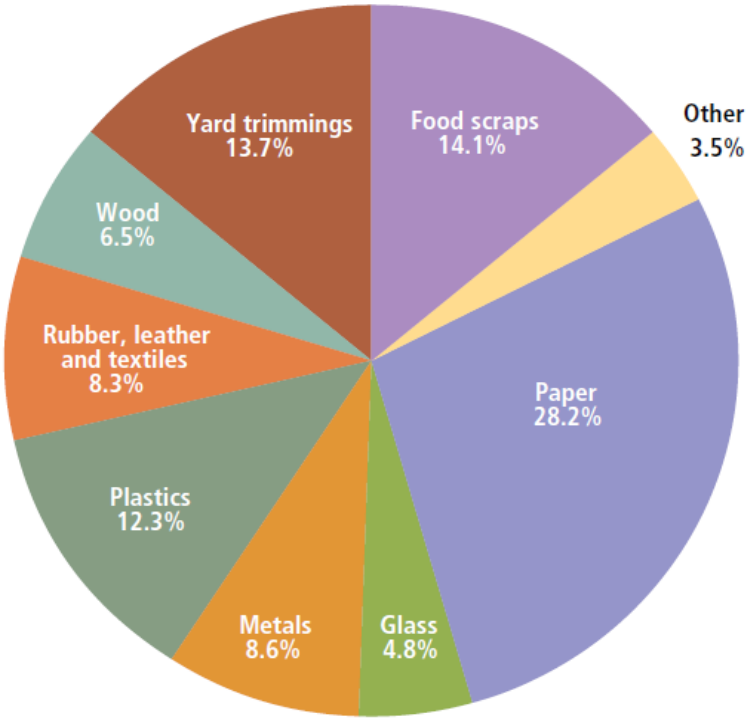


WORLD RECOVERED PAPER STATISTICS BY REGION 2010 - 2011 (1,000 tonnes)

	Recovery		Imports		Exports	
	2010	2011	2010	2011	2010	2011
Asia	87,883	91,447	34,301	36,694	6,956	7,247
Europe	63,382	64,070	15,060	15,867	23,086	24,920
North America	51,123	52,384	1,769	1,738	20,640	22,962
Latin America	10,925	11,464	2,173	2,128	729	920
Oceania	3,650	3,610	3	3	1,634	1,578
Africa	2,447	2,451	32	29	102	142
Middle East	2,416	2,751	176	241	590	720
Total	221,825	228,176	53,515	56,700	53,736	58,489

MSW by Material Before Recycling

Figure 5. Total MSW Generation (by material), 2009
243 Million Tons (before recycling)



Source: EPA
Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2009

Recycled Fiber Definitions

- **Recovery Rate (RR)**
  - *how much wastepaper is diverted from landfill*

$$RR = 100\% \frac{\text{Tons of Wastepaper Collected}}{\text{Tons of Paper Consumed}}$$

- **Utilization Rate (UR)**
  - *fraction of recycled fibers contained in paper*

$$UR = 100\% \frac{\text{Tons of Wastepaper Consumed at Mills}}{\text{Tons of Paper Produced}}$$

Products with highest % recovery.

- Lead acid batteries, 96%
- Corrugated boxes, 85%
- Newspapers, 72%
- Steel packaging, 69%
- Major appliances, 65%
- Yard trimmings, 58%
- Aluminum cans, 50%
- Mixed paper, 45%
- Tires, 35%
- Glass Containers, 31%
- HDPE, milk containers, 29%
- PET Bottles, 28%

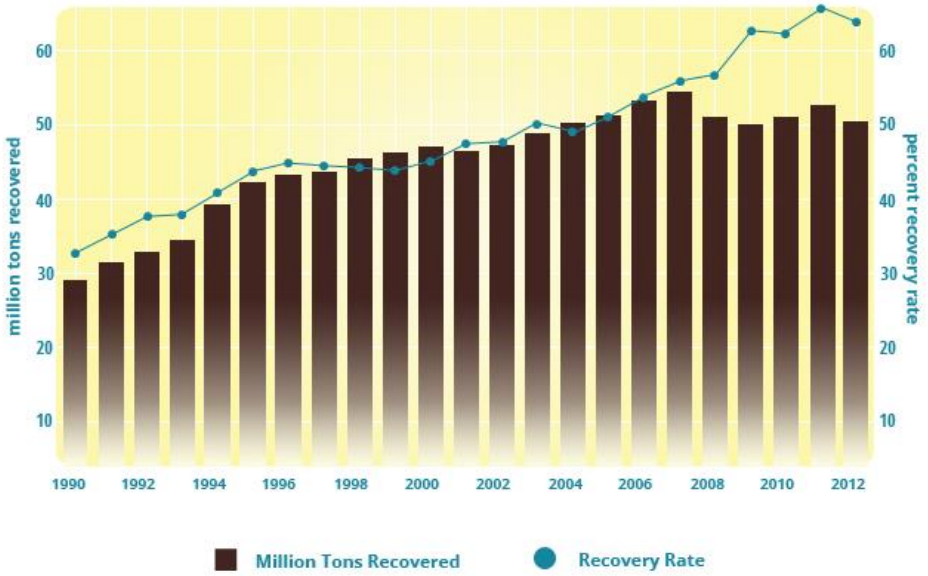
Source: Wikipedia

Source: EPA

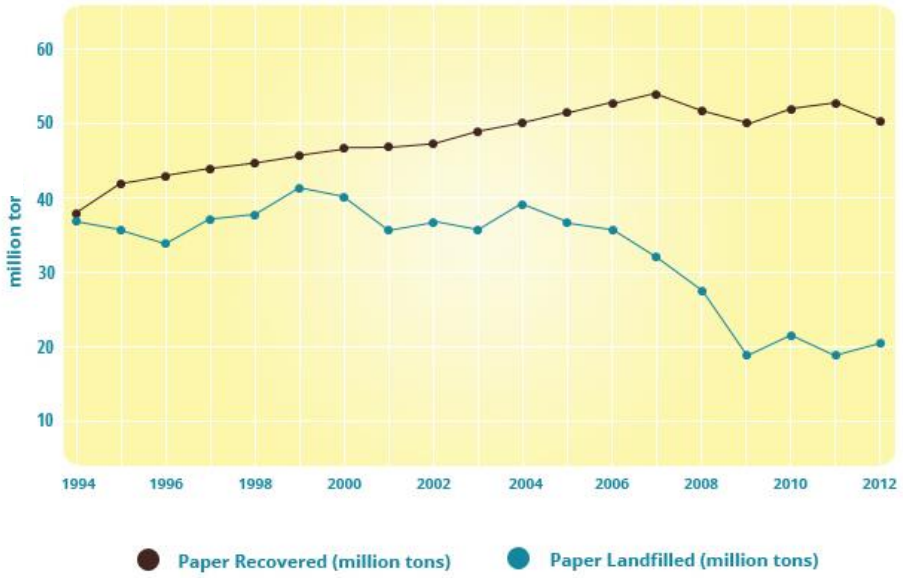
Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2009

US Recovery of Paper Positively Impacts Landfill Volume

Paper/board Recovery Rate in the US:

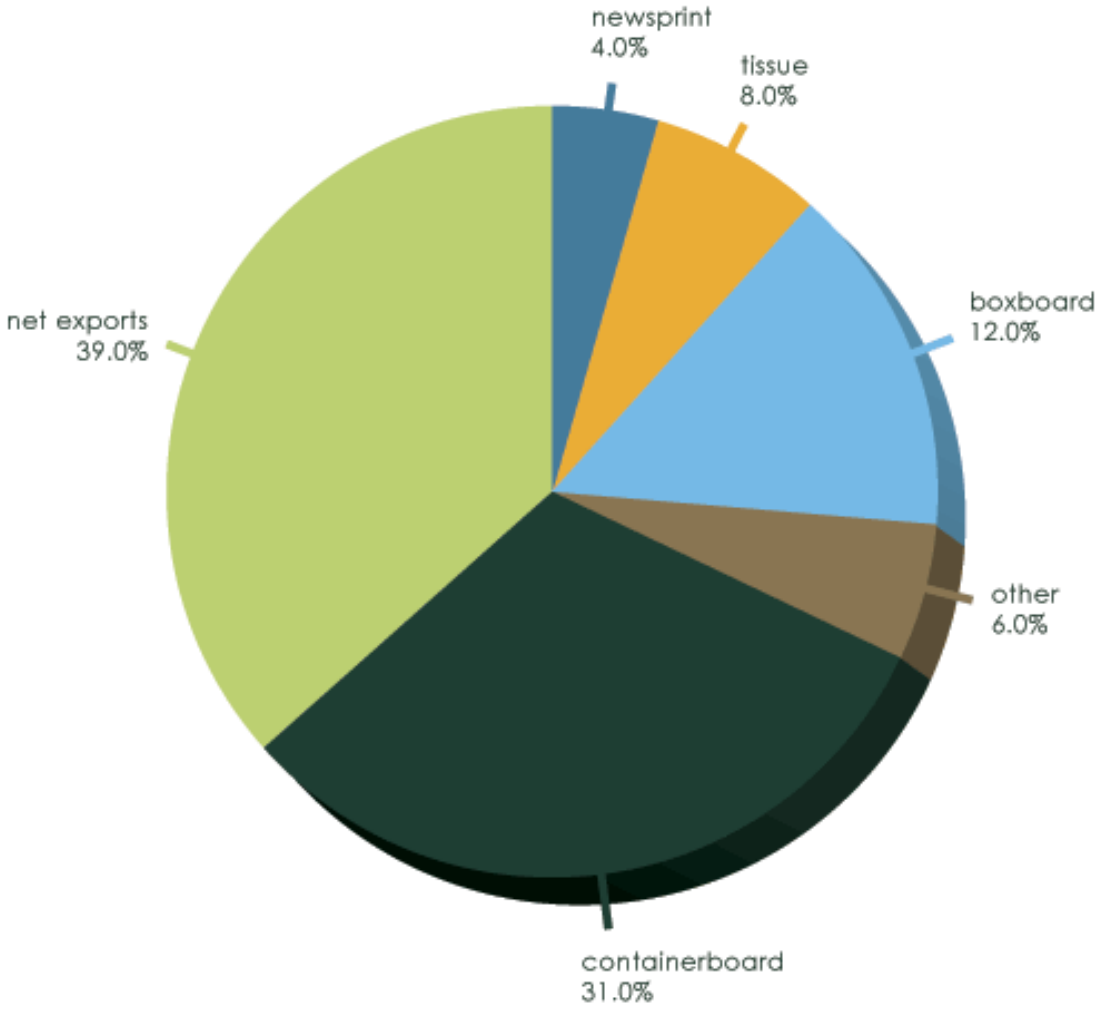


Recovered and Landfilled Paper

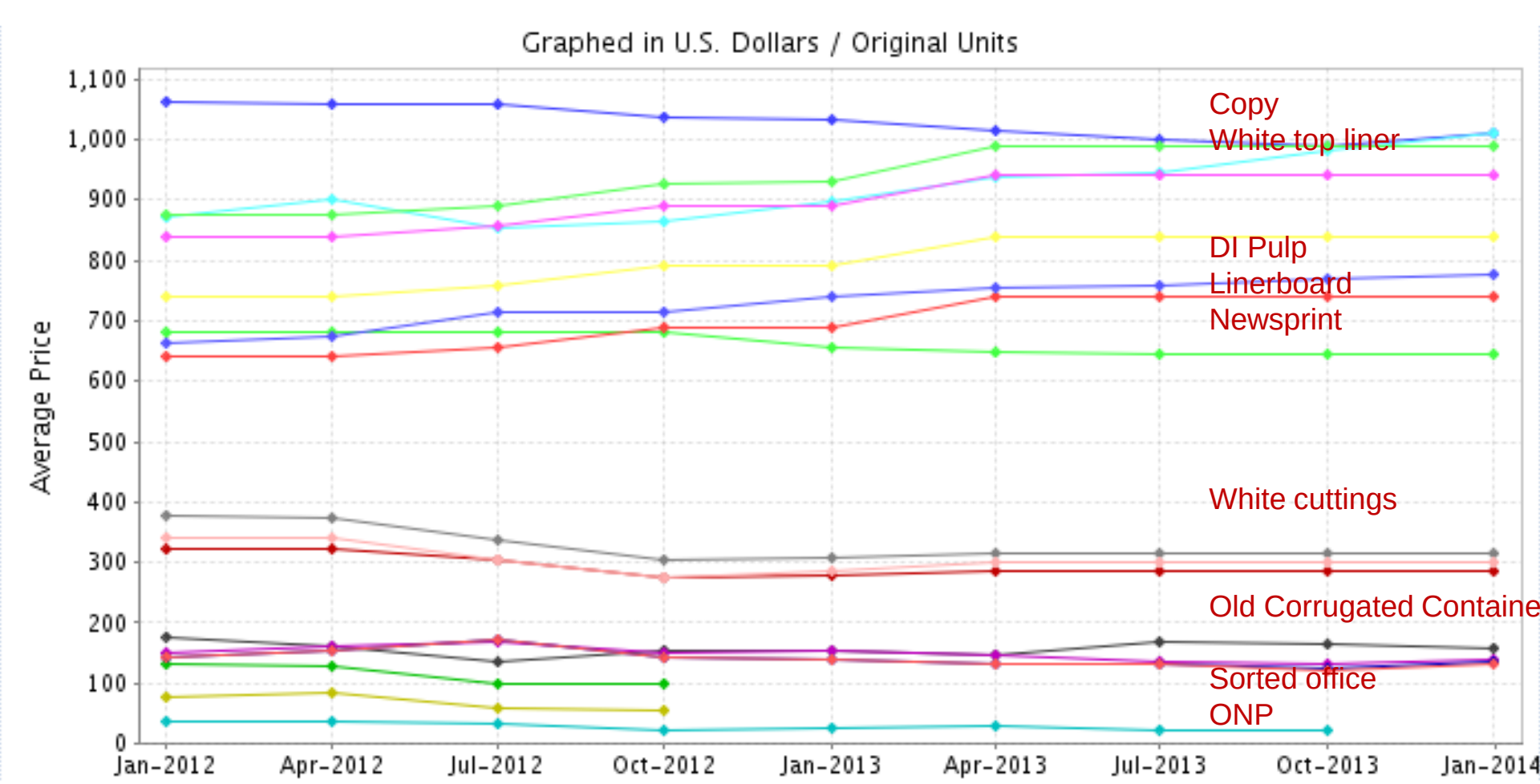


Source: afandpa.org, 2011

Where US Recovered Paper Goes:



Source: afandpa.org, 2011


Graphed in U.S. Dollars / Original Units
Average Price
1,100
1,000
900
800
700
600
500
400
300
200
100
0
Jan-2012
Apr-2012
Jul-2012
Oct-2012
Jan-2013
Apr-2013
Jul-2013
Oct-2013
Jan-2014
Copy
White top liner
DI Pulp
Linerboard
Newsprint
White cuttings
Old Corrugated Containe
Sorted office
ONP

Paper Recycling Operations

- **Why is it easy to recycle paper?**
  - There is no glue holding fibers together
  - Put paper in water and the fibers come apart
  - Remove water and you can form paper that is bonded

- **Why is it hard to recycle paper?**
  - Lots of contaminants
    - Large junk, plastic, foil, adhesives (stickies), inks, glass…..
  - Certain fibers & coatings act as contaminants if mixed in with other types of fibers
  - Can be expensive relative to virgin paper from wood
  - Hard to meet optical, cleanliness, strength properties

Collection of Recovered Paper: Sources

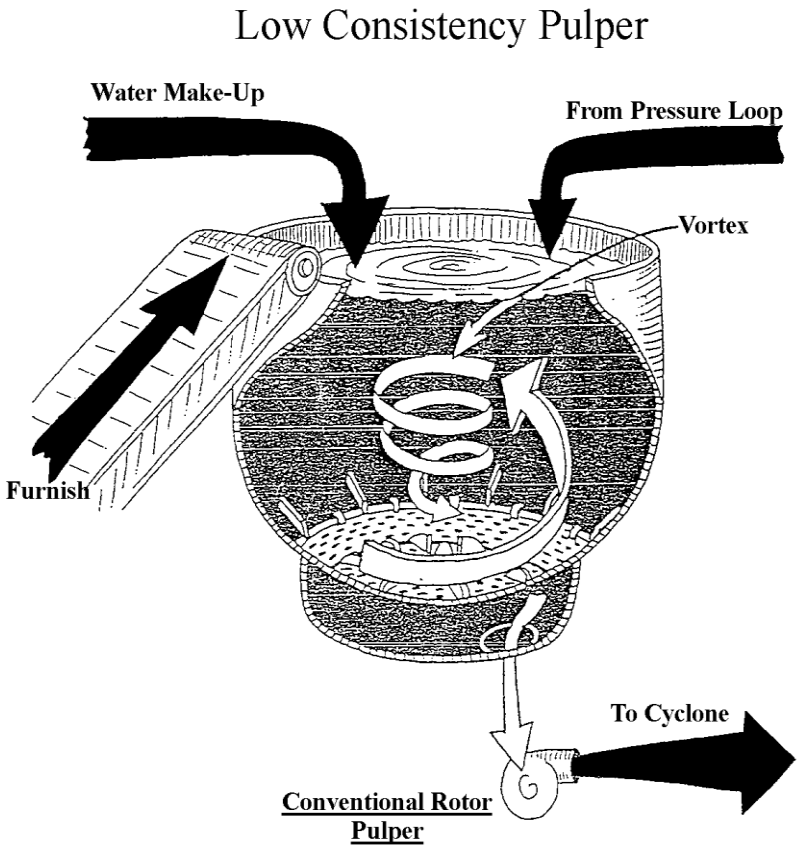
- Recovered paper dealers or brokers
- From paper converting facilities
- From large office complexes
- From stores
- From individuals in their private vehicles
- From material recovery facilities
  - Municipal waste that is sorted for glass, metal, plastics and paper….
  - Single stream sourcing is becoming more popular because it increases yield, municipalities love it!!!!!
  - Single stream sourcing introduces issues to the paper recycling mill (glass)

Major Recycling Unit Operations

- Pulping
- Cleaning
- Screening --- these three ops are enough for boxes
- Deinking --- needed for printing or tissue
  - Washing
  - Flotation
- Dispersion and Kneading
- Bleaching --- often needed for printing or tissue
- Water Treatment
- Solid Waste Handling

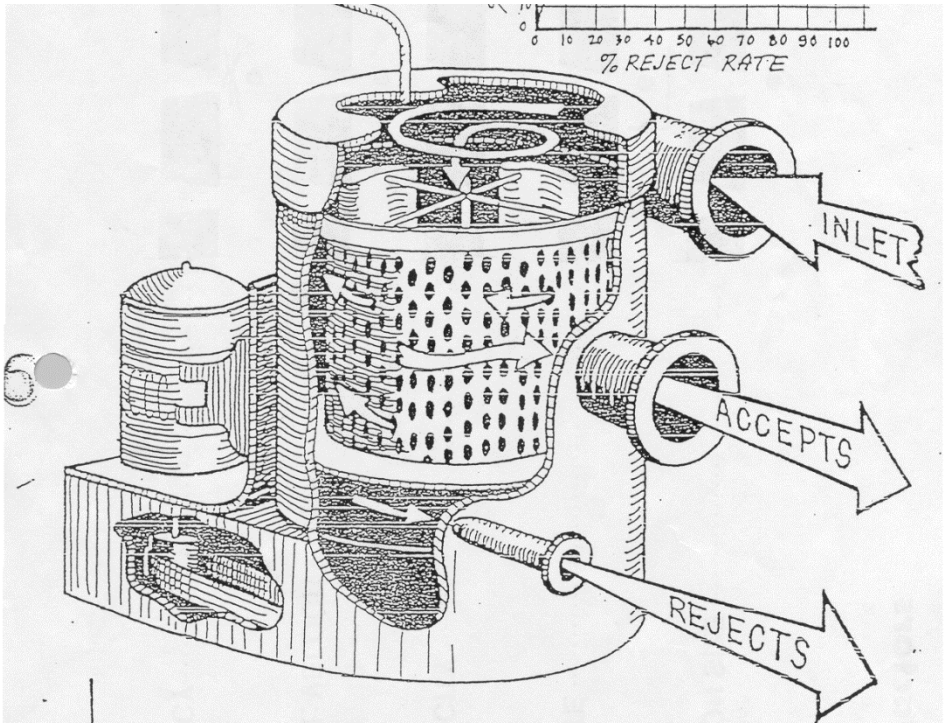
Pulping

- Water breaks hydrogen bonds between fibers
- Motion of rotor causes a vortex of pulp stock. The baffles are used to improve mixing.
- High mechanical force due to impacts of rotor separate fibers
- Possibility to damage fibers



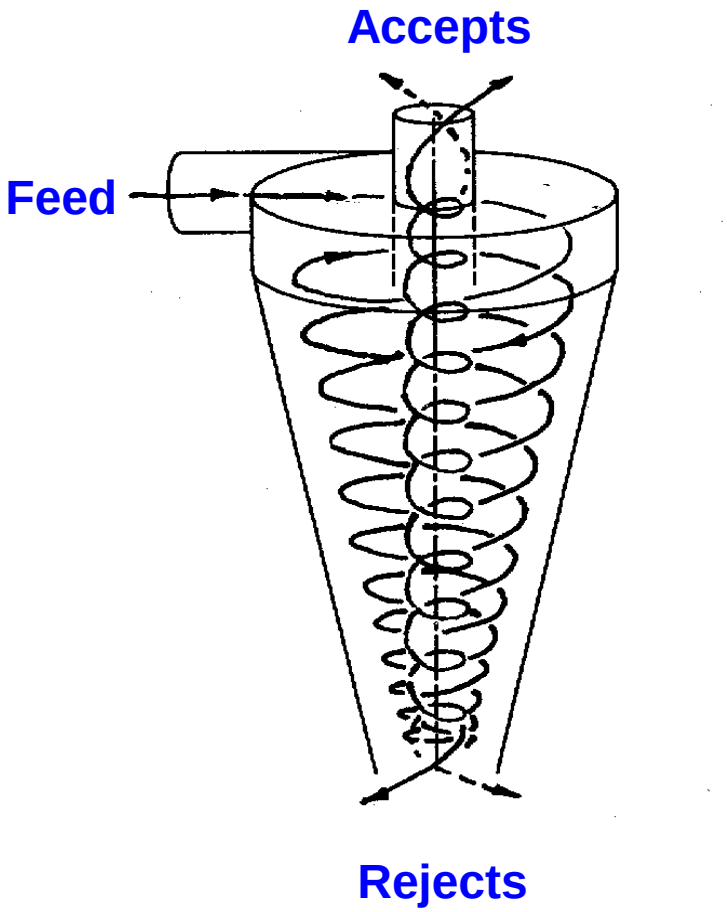
Screening

- Screening separates contaminants based mainly on **size**, but also on shape and deformability
- A barrier that rejects large contaminants and lets fibers pass
- Produces solid rejects (1% or so)



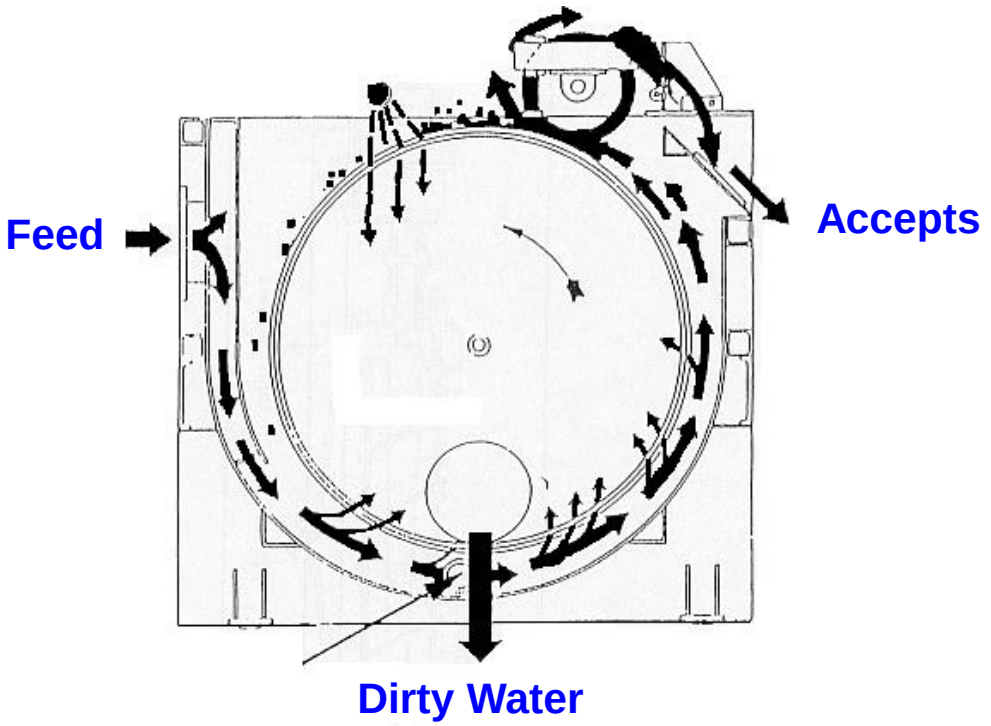
Centrifugal Cleaner: Features and Flow

- High density contaminants are slung to outside and out rejects port (bottom)
- good fibers stay in middle and go out accepts (top) port
- Solid Rejects from cleaner systems (1%)

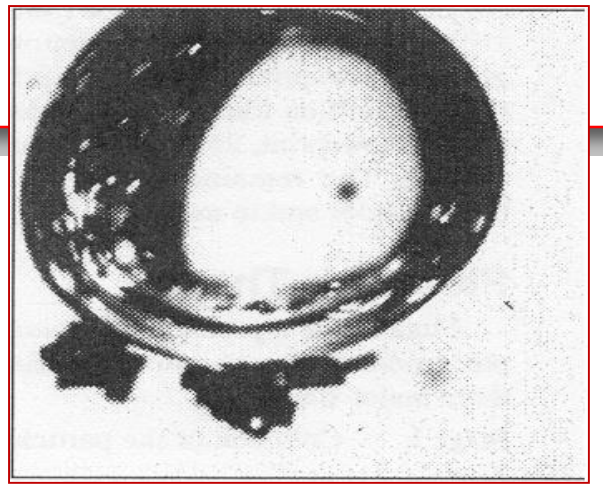


Washers

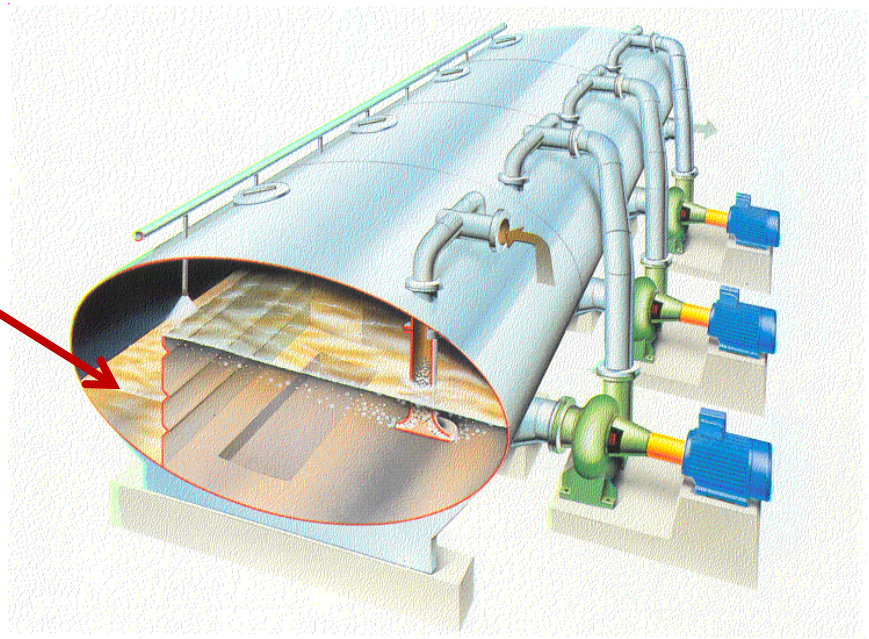
- **Definition**: a separation device that rinses small particulate contaminants away from fiber while minimizing fiber loss
- Washing wire allows small contaminant particles to pass but retains fibers (opposite of screening)
- Dinking Washer
  - Dilute pulp with wash water
  - Disperse small contaminant in water phase
  - Remove contaminant laden water
  - Always a compromise between fiber/fine loss and ink removal
- Solids washed through the screen, fine rejects, 5-15% roughly



Flotation

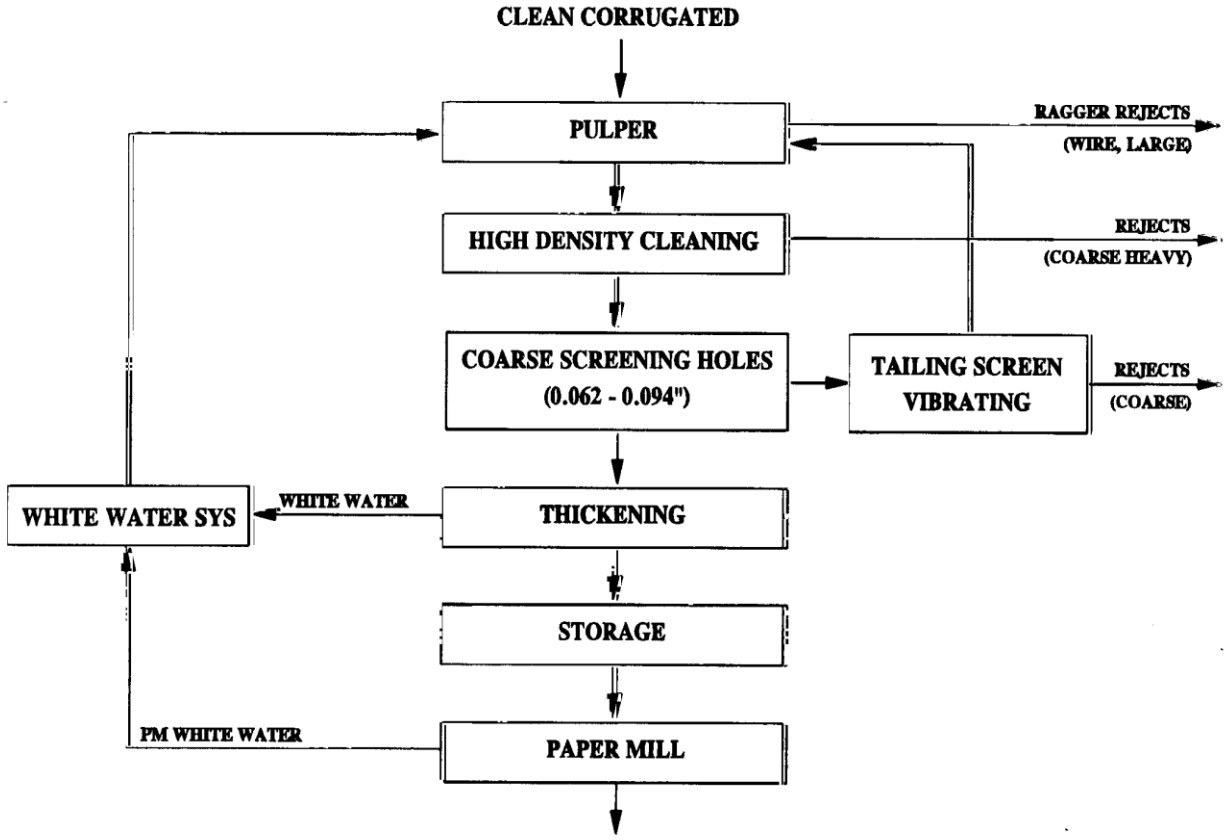


- **Definition**: a process in which hydrophobic contaminants are preferentially removed from a pulp stock by attachment to air bubbles.
- Air bubbles contact inks and remove them with foam that is rejected
- Solid rejects, 1-5% roughly

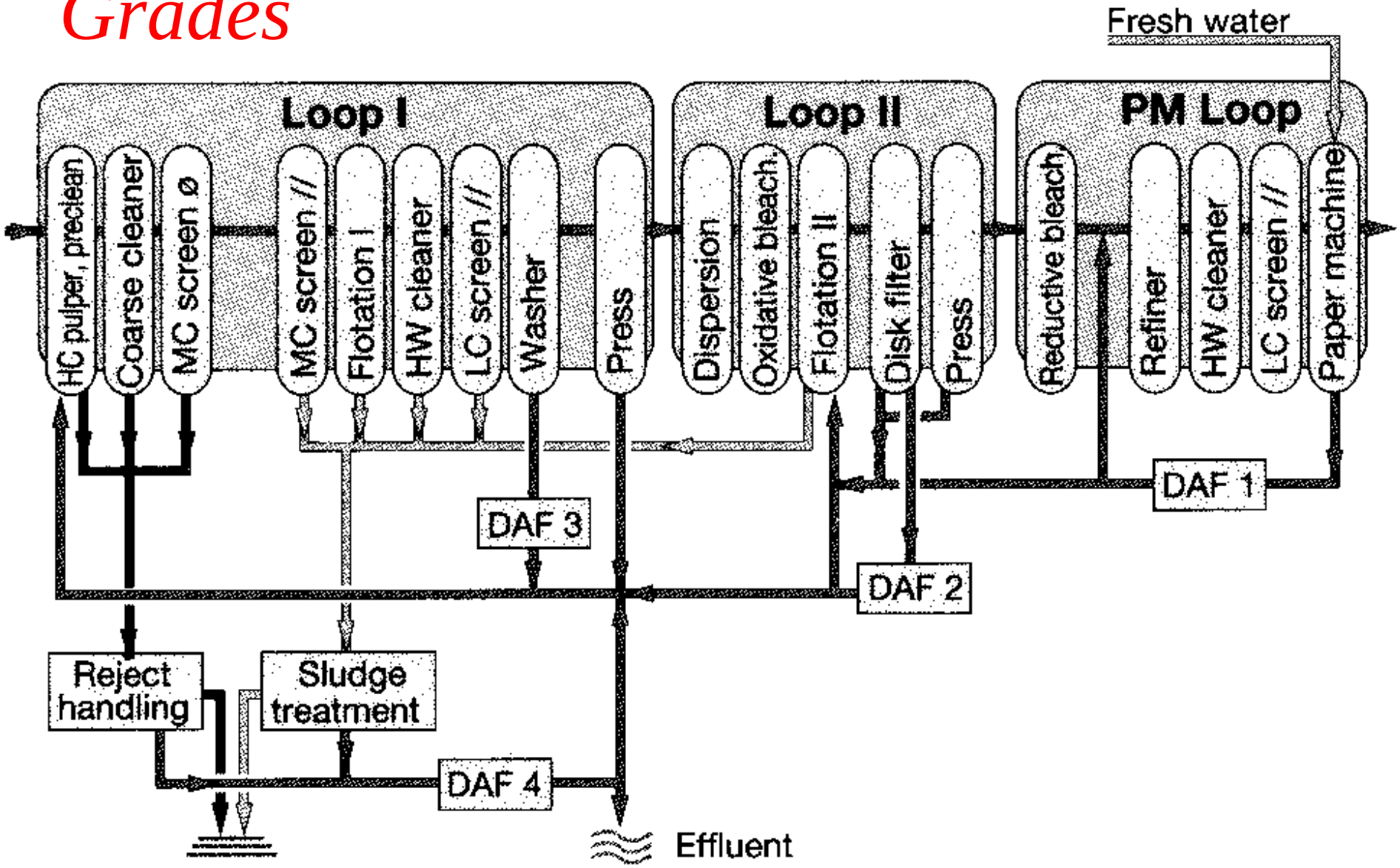


Simple Cleaning System for Packaging Product

- Used to produce liner, medium, folding board, tube stock
- Often used with a continuous pulper
- Yield?
- Contaminant removal?
- Ink removal?



High Grade Printing and Writing Grades



Amount of Rejects and Sludges from Recycling:

- *Printing Writing:*
- *Tissue Paper:*
- *Corrugated box:*
- *Shoe/cereal box*

Produced paper	Recovered paper grade	Amount of total waste [% by dry weight]
Graphic paper	News, magazines	15–20
	Superior grades	10–25
Hygienic paper	Files, office paper, ordinary, medium grades	28–40
Market DIP	Office paper	32–40
Liner, fluting	Sorted mixed recov. paper, supermarket waste	4–9
Board	Sorted mixed recov. paper, supermarket waste	4–9

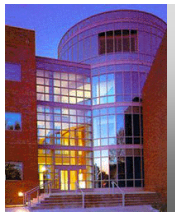
How many times can paper be recycled?

- Not easy to determine, depends on type of fiber also
- If we assume that 20% of our fibers are lost on average during a recycling process
- Crudely, a fiber is recycled about 4-5 times before it ends up in the rejects of a recycling process

Section Summary

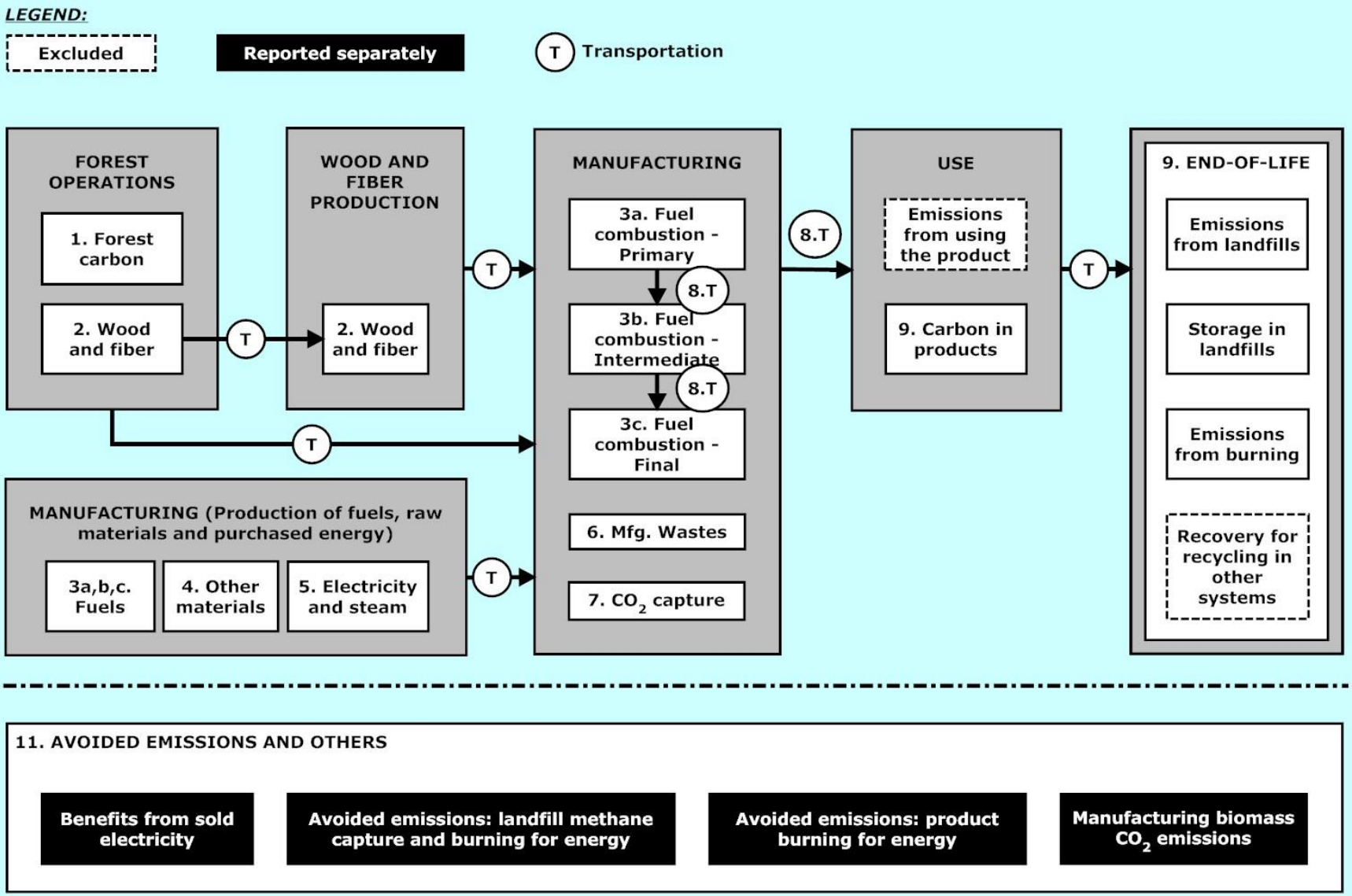
- Paper recycling is more than 50% of entire paper industry
- Papers are sorted based on type of pulp fiber
  - Cross-contamination of different fibers reduces value of recovered paper
- High demand for recovered paper and it's very economical
- Recycling operations involve contaminant removal and generates solid waste
- Paper making fibers wear out after multiple use. It's necessary to replace these fibers with virgin fibers

Questions?



6. Environmental LCA of Paper

Life Cycle Stages of Paper



Data and Graphs from NCASI LCA P&W Grades, 2010 Software used from NCASI, FEFPRO

Summary of key points of LCAs of paper

- Paper has an advantage over petroleum products in that it is renewable and biodegradable
- Petroleum products tend to have several environmental advantages in other LCA impact categories
- One must note that plastics and paper often have different function and performance that makes some comparisons very complex.
- In general, recycled paper many environmental performance impacts (but not all) than virgin paper
- Strong caution, virgin and recycled fiber are part of the same life cycle and it is strictly not fair to compare them against each other, also highly controversial with respect to allocations of burdens (see later) (also see: *Effect of life cycle analysis methodology choices on the environmental life cycle analysis results for recyclable paper products, White Paper* revised January 7, 2012, a discussion of three major LCA studies for paper products, a discussion about recycling allocation methods, and an in-depth investigation of the carbon footprints of coated freesheet and coated mechanical sheet. Powerpoint presentation based on the document appears in above list as LCA of Paper Products. http://www4.ncsu.edu/~richardv/presentations.html)

Summary of key points of LCAs of paper

- Paper products consume wood and the associated lands to grow it
  - This is good in developed countries – encourages more forests
  - This can have issues in developing countries if wood is not sustainably sourced
- Life-cycle stages
  - Raw materials such as wood and water impact GWP and water footprint
  - Manufacturing process significantly impacts many environmental categories
    - *Purchase chemicals and fuels*
  - Use phase not so important
  - Transportation phase not so important
  - End-of-life could be very important, especially concerning GWP
    - *Assumption whether paper decays in landfills is critical*

Full Life Cycle Analysis of Paper

Catalog weighs 0.135 kg.

Table ES-6. LCIA Results – Catalog, Coated Freesheet

Impact category	Unit	Total (unit/ catalog)	1- Fiber procurement	2- Coated freesheet production	3- Production of catalogs	4- Transport and use	5- End-of-life	Storage in use and landfill
Global Warming (GW)	kg CO_2 eq.	4.89E-01	5.4%	43.6%	15.7%	1.2%	37.7%	-3.4%
Acidification (AC)	H^+ moles eq.	1.67E-01	7.6%	67.4%	21.1%	1.1%	2.9%	
Respiratory effects (RES)	kg $PM_{2.5}$ eq.	6.52E-04	3.5%	77.9%	15.6%	0.3%	2.6%	
Eutrophication (EU)	kg N eq.	8.85E-04	1.9%	19.0%	6.2%	0.2%	72.8%	N/A
Ozone depletion (OD)	kg CFC-11 eq.	2.63E-08	6%	53%	31%	4%	7%	
Smog (SM)	kg NOx eq.	2.10E-03	7.7%	36.4%	48.7%	1.8%	5.3%	
Fossil fuel depletion (FF)	MJ surplus	3.94E-01	9.3%	52.4%	29.8%	2.6%	5.9%	

[1] Results obtained using the *ecoinvent* database only (see Section 9.3.1.2 for more details)

GWP of a plastic is about 0.9 kg CO2/.135 kg, about **twice** that of paper.

National Council for Air and Stream Improvement, Inc. (NCASI). 2010. *Life cycle assessment of North American printing and writing paper products*. Unpublished Report. Research Triangle Park, NC: National Council for Air and Stream Improvement, Inc.

Life Cycle Analysis of Kraft Pulp

Table 9: Relative Contribution of Process Inventory to Environmental Impact Categories. Data is based on the SOL-P scenario. Other scenarios are consistent with these results.

Total Emissions	NaOH, 50%	CaO	H_2O_2, 50%	H_2SO_4	$NaClO_3$	CH_3OH	CO_2 (gas)	NG	DE	SW	Solid Residue	Transport, Raw Matls.	Transport, Feedstock
GW	10%	6%	3%	1%	22%	0%	4%	84%	720%	-757%	0%	1%	7%
AD	4%	0%	1%	6%	8%	1%	1%	58%	1%	16%	0%	1%	4%
CG	9%	0%	4%	2%	39%	0%	3%	28%	0%	2%	11%	0%	1%
NCG	3%	0%	5%	1%	46%	1%	1%	42%	0%	1%	0%	0%	0%
RE	6%	1%	1%	7%	13%	1%	1%	63%	0%	5%	0%	0%	2%
EU	9%	1%	2%	2%	16%	0%	3%	13%	0%	14%	35%	1%	4%
OD	8%	5%	4%	1%	16%	1%	4%	43%	0%	0%	1%	2%	15%
EC	18%	1%	12%	1%	50%	0%	3%	10%	0%	3%	1%	0%	1%
SM	4%	1%	1%	1%	8%	0%	1%	21%	0%	50%	0%	2%	12%

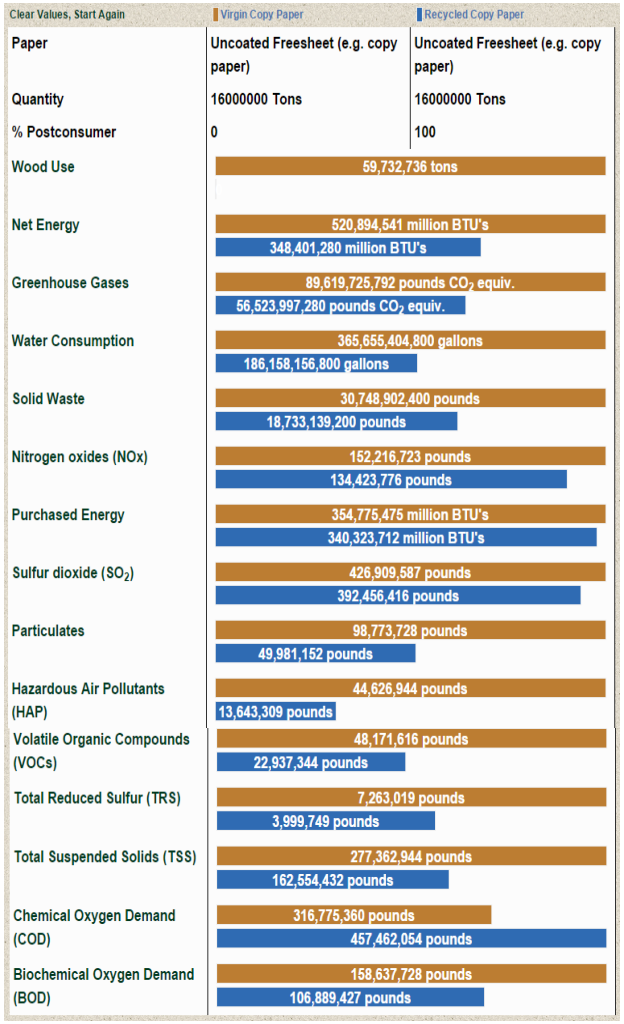
Venditti and coworkers LCA on softwood bleachable grades (Culbertson et al, 2015)

Virgin v. Recycled Products

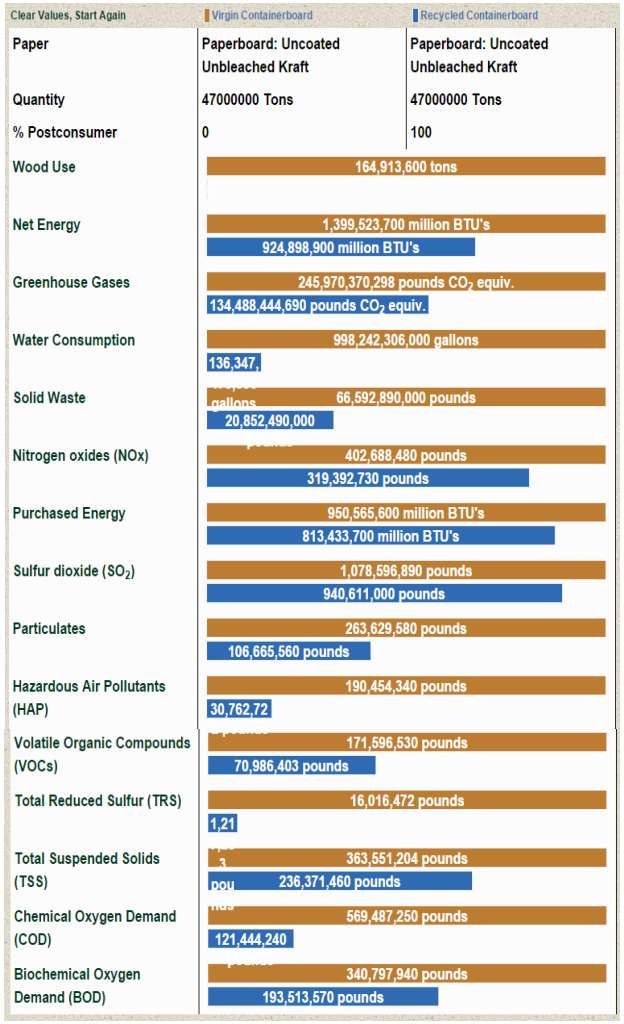
- Recycled is more effective in reducing environmental impacts in many categories relative to virgin paper
- However, it must be understood that
  - Recycled Fibers wear out in recycling, there must be virgin fibers to replace them
  - Recycled fibers would not exist without the existence of virgin fibers
  - For many high performance products virgin fibers are preferred
    - *recycled fibers simply are not suited for the application*
    - *Due to the cost and the environmental impacts of upgrading the recycled fibers their use is not warranted*
  - Recycled fibers have environmental impacts themselves
- We need virgin fibers and need to use recycled fibers in a smart way

Recycled saves in many categories

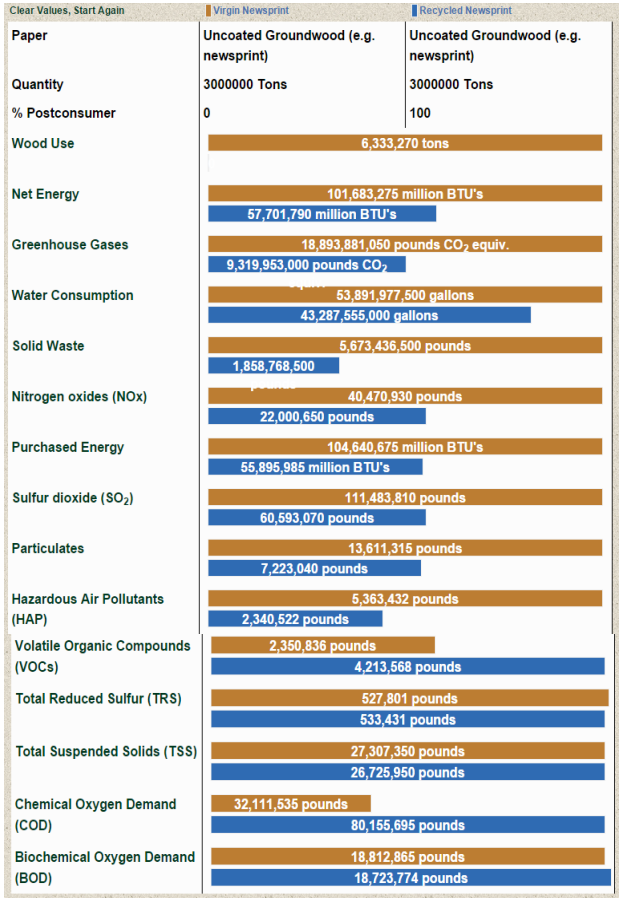
Copy Paper



Unbleached Board



Newspaper Print



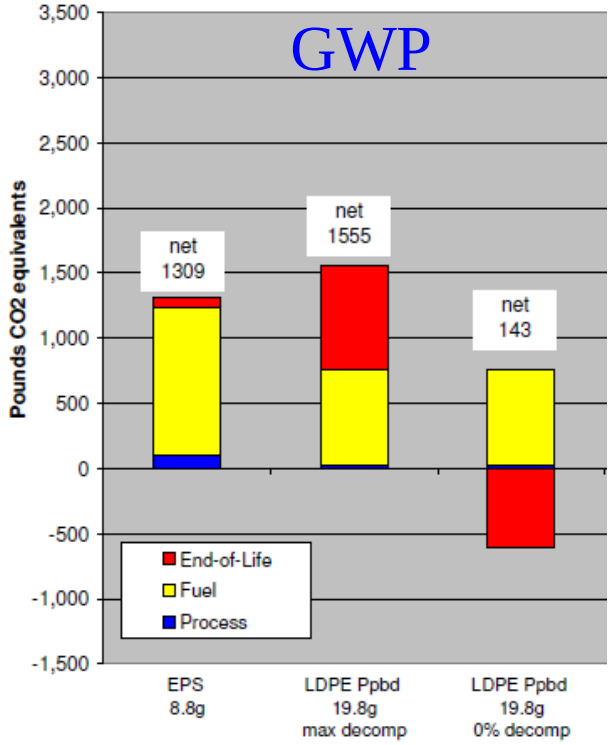
Environmental Paper Network

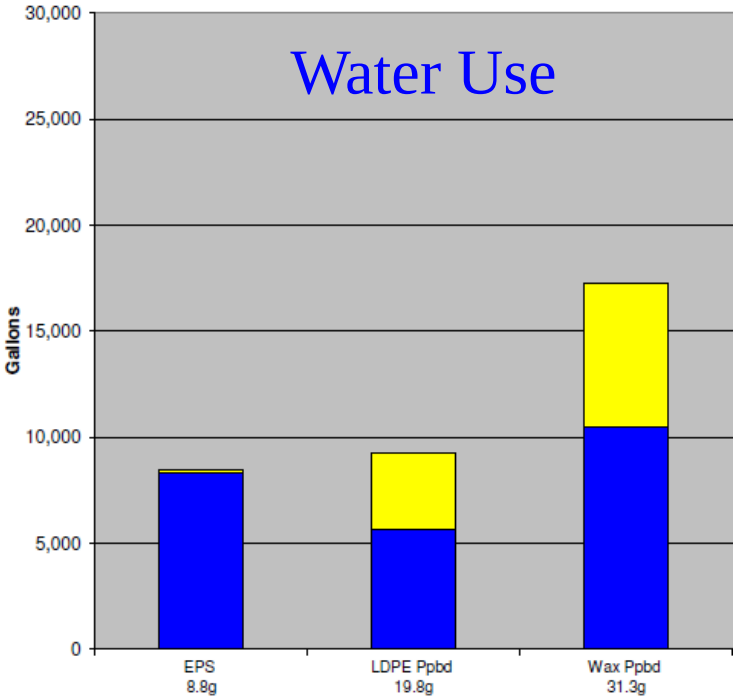
Paper v. Plastic

- Polystyrene foam, poly coated paper, wax coated paper, solid PLA cold cups
- Functional unit: 10,000 cups
- Focus on energy, solid waste, GWP, water use
- Life cycle inventory of foam PS, Paper based, and PLA foodservice products, Franklin Associates, 2011.

Paper v. Plastic Tradeoffs

- Results show polystyrene foam to have lower energy, water and waste
- Results show paper to have lower GWP
- Polystyrene foam is not renewable or biodegradable
- Paper is from a renewable resource and is biodegradable





10,000 cups

Section Summary

- Paper has an advantage over petroleum products in that it is renewable and biodegradable
- Petroleum products tend to have several environmental advantages in other LCA impact categories
- In general, recycled paper has better environmental performance than virgin paper
- Paper products consume wood and the associated lands to grow it
  - This is good in developed countries – encourages more forests
  - This can have issues in developing countries if wood is not sustainably sourced
- Manufacturing and end-of-life are critical life-cycle stages

Questions?

Thank you! Final Questions?

Dr. Richard Venditti

Paper Science and Engineering

NC State University

***E-mail**: richardv@ncsu.edu*

***Website**: Go.ncsu.edu/Venditti*

Thanks to Dr. Byrd, Dr. Pawlak and Dr. Jameel for allowing the use of their slides.