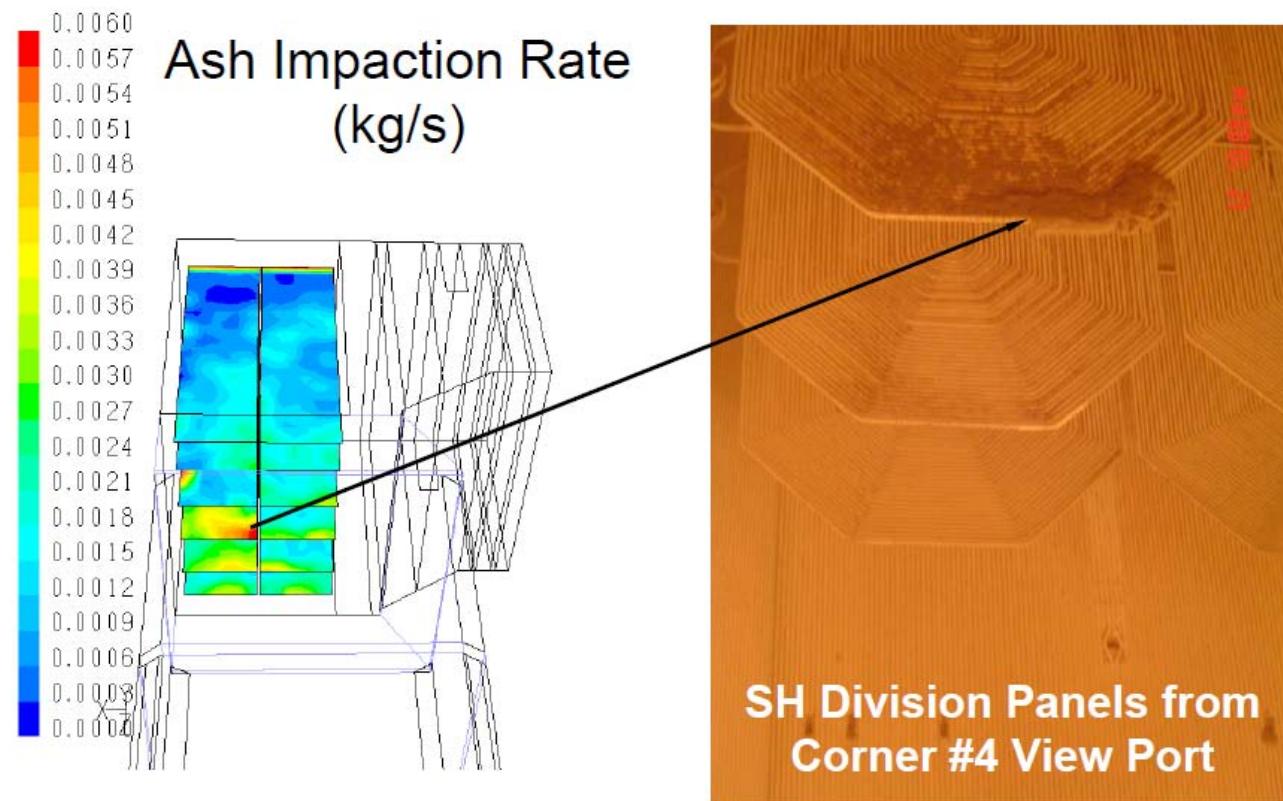


Ash Fouling and Slagging Model

Columbia 2: Deposit Pattern



Furnace Wall Cleaning Strategy

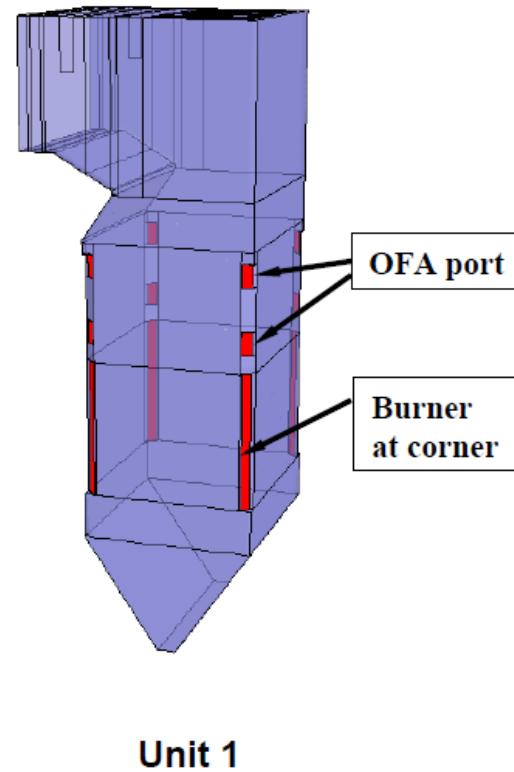
Objectives

- Evaluate design and operating condition impact on furnace slagging
 - OFA
 - Primary air and Aux air
- Optimize sootblowing frequency and pressure:
 - Low pressure high frequency vs. high pressure low frequency
- Optimize blowing configuration:
 - Blowing angle

Furnace Wall Cleaning Strategy

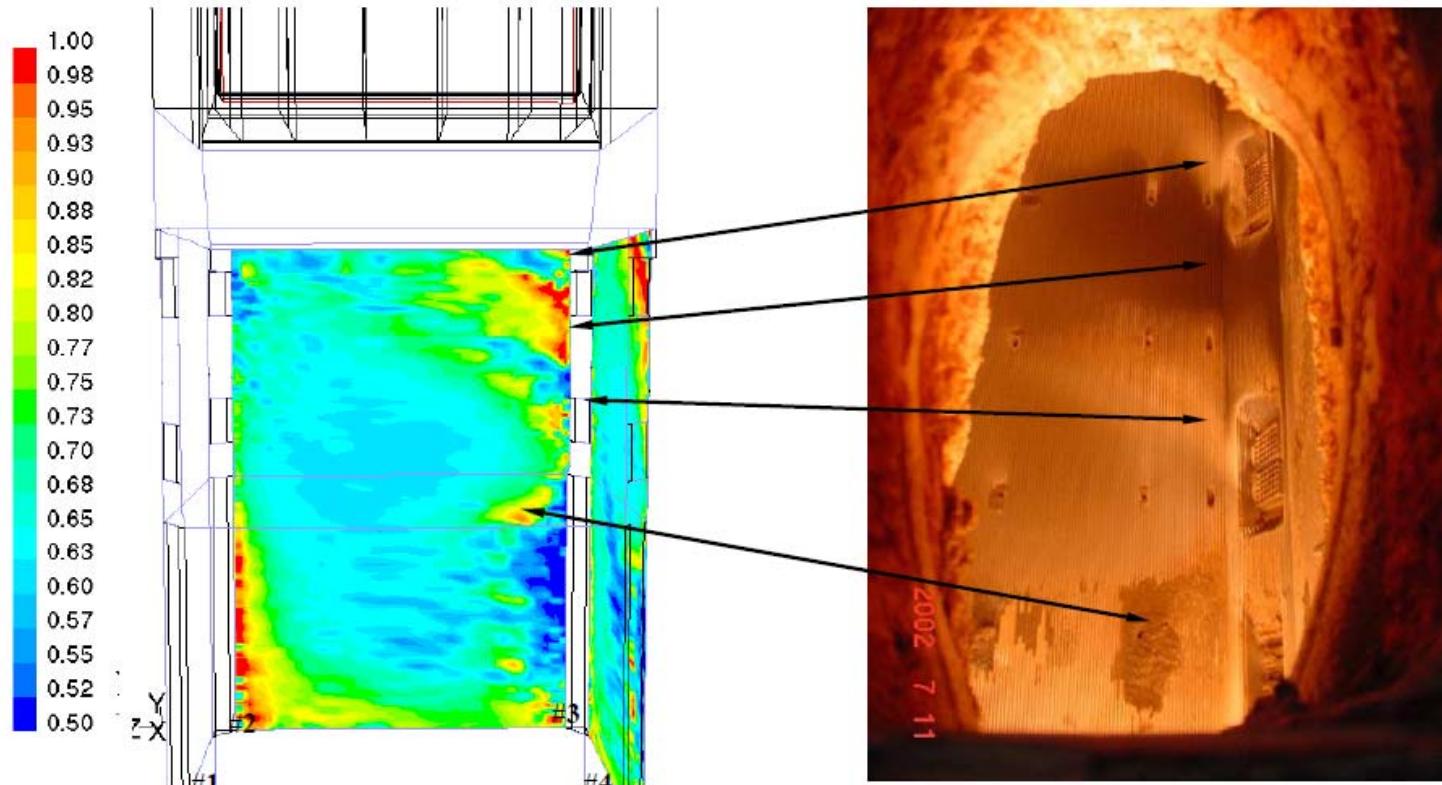
CFD Model of a T-fired Boiler Furnace

- Four corner tangentially-fired boiler at Columbia Energy Center
- 512 MW nameplate capacity
- Average monthly capacity factor:
 - Unit 1 = 95% (last 2 months)
 - Unit 2 = 98% (last 2 months)
- Coal - Powder River Basin (PRB)
 - Eagle Butte coal
- OFA design:
 - Unit 1: OEM design
 - Unit 2: RMT design



Furnace Wall Cleaning Strategy

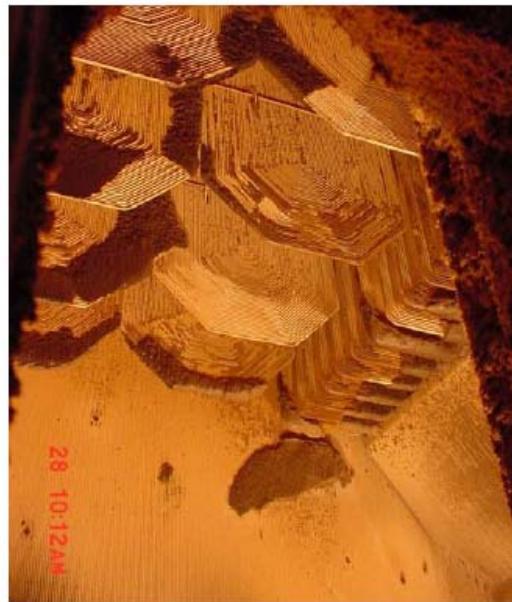
Furnace Wall Slagging Deposit



Deposit thickness (inch) 6 hour operation w/o Sootblowing

Furnace Wall Cleaning Strategy

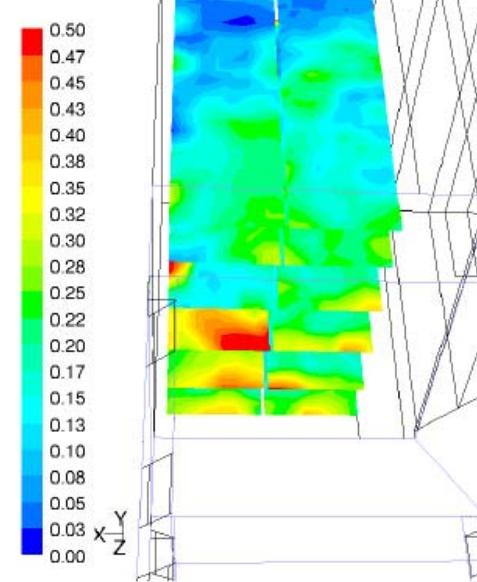
SH Division Panel Slagging Deposit



Picture taken on
Feb 28th, 2007

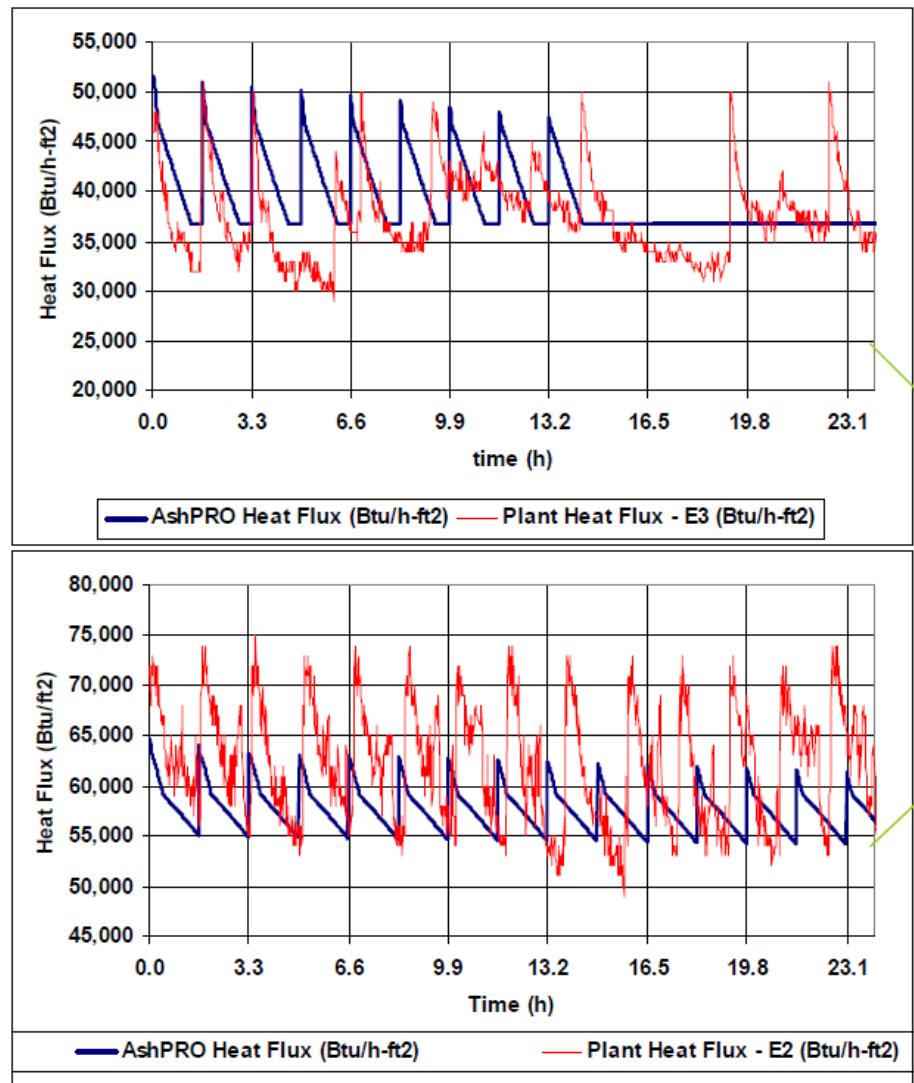


Picture taken on
March 3rd, 2007

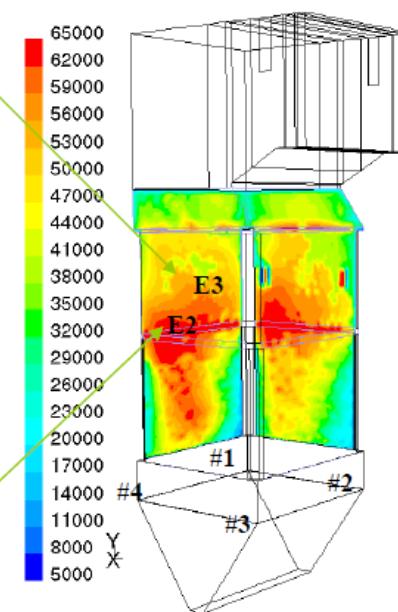


Deposit thickness (inch)
one-hour operation
w/o sootblowing

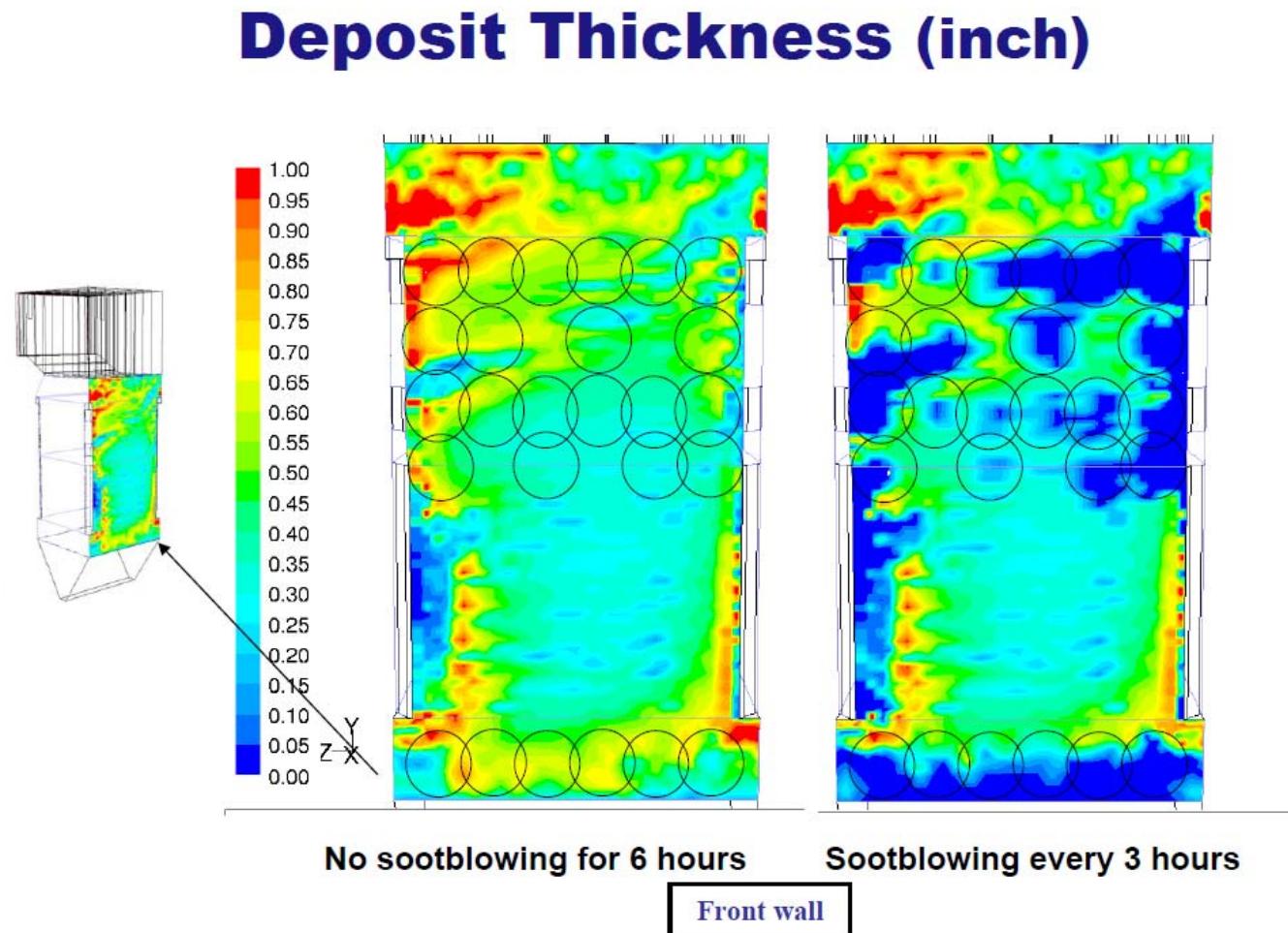
Furnace Wall Cleaning Strategy



Heat Flux Data Comparison

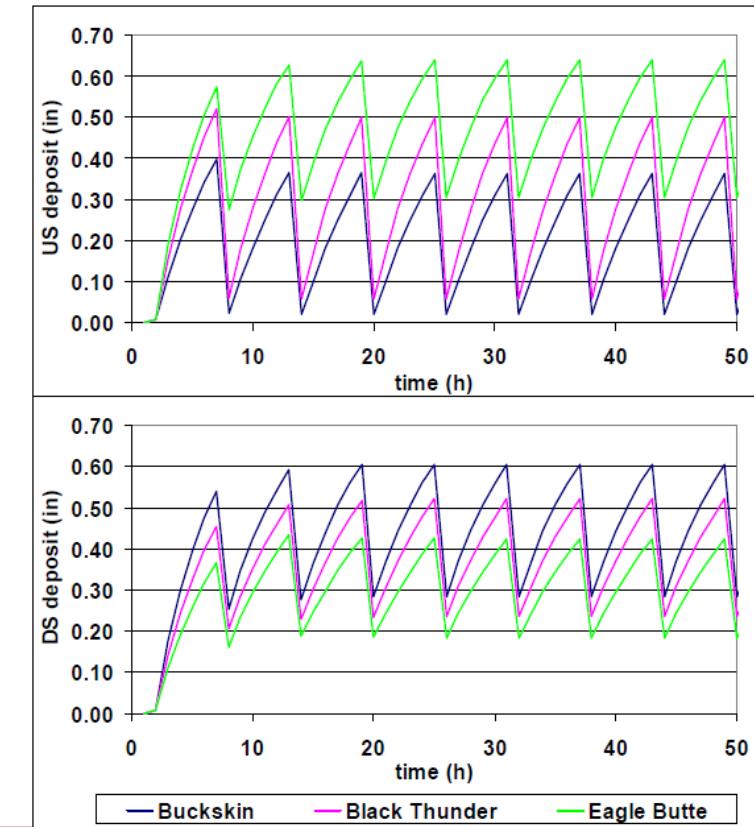


Furnace Wall Cleaning Strategy



Furnace Wall Cleaning Strategy

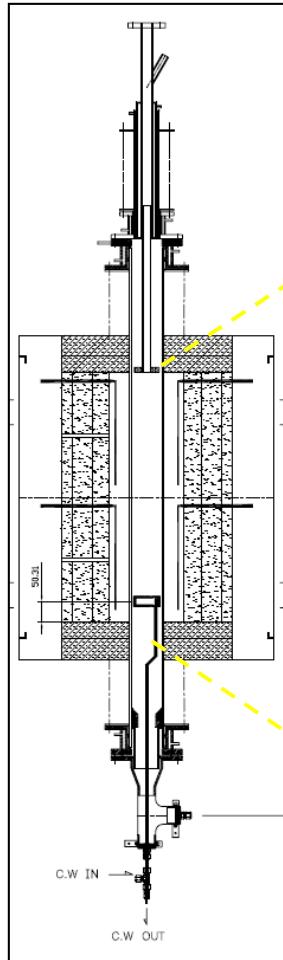
Low Temp Fouling Deposit Growth and Removal for Different Coals



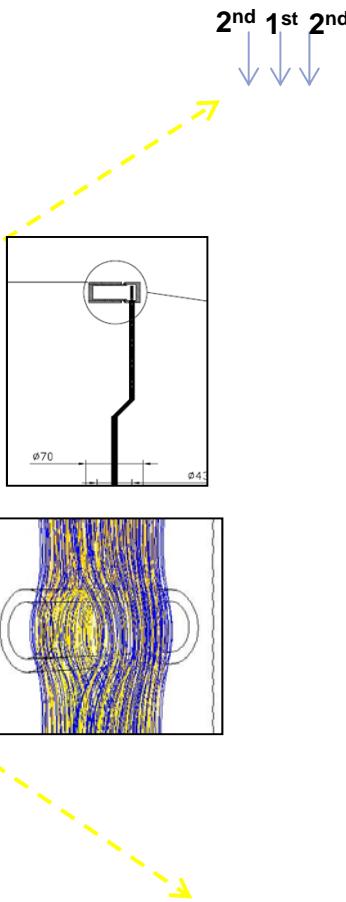
- Final SH pendant
 - Local flue gas temperature is ~ 1,500 °F
 - Sootblowing frequency: every 6 hours
- Upstream deposit
 - Deposit growth: Eagle Butte > Black Thunder > Buckskin
 - Buckskin and Black Thunder are easier to clean with sootblowing
- Downstream deposit
 - Deposit growth: Buckskin > Black Thunder > Eagle Butte
 - Deposit is hard to clean with sootblowing for all three coals

40

State of the Art in PNU



<DTF experiment>



<Simulation>

Ch. 2 Solid Fuels by Prof. Jeon

Condition	
Environment T.	1300 °C
Feeding rate	0.15g/min
1 st air	N2 = 1.5(lpm)
2 nd air	O2+N2 = 3.5(lpm)
Time	1h

Coal property		
	Collie	Coal B
Tcv(K)	1406K	1325K
Ash(%)	13.4%	5.7

Melting temperature(K)	
SiO ₂	1873
Al ₂ O ₃	2345
TiO ₂	2116
Fe ₂ O ₃	1839

	Collie	Coal B
SiO ₂	0.416832	0.4352
Al ₂ O ₃	0.224953	0.2643
TiO ₂	0.017431	0.0066
Fe ₂ O ₃	0.143851	0.1422
CaO	0.018692	0.0443
MgO	0.011546	0.0191
Na ₂ O	0.001779	0.0357
K ₂ O	0.009301	0.0123
P ₂ O ₅	0.003665	0
MnO	0.000765	0
FeO	0	0
NiO	0	0
ZrO ₂	0	0
CaF ₂	0	0
B ₂ O ₃	0	0
SO ₃	0.149675	0.0163

1. from Solid Fuel

State of the Art in PNU

■ Deposition experiment results

Collie



Coal B

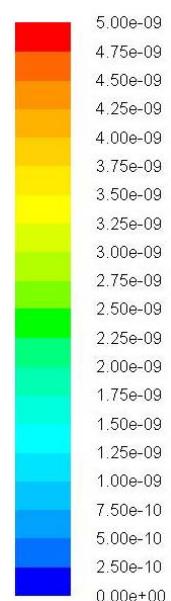


$$CE = \frac{m_{Dep}}{m_{Ash} \frac{A_{mullite}}{A_{reactor}}} 100 \quad [\% \text{ kg}_{Dep}/\text{kg}_{Ash}]$$

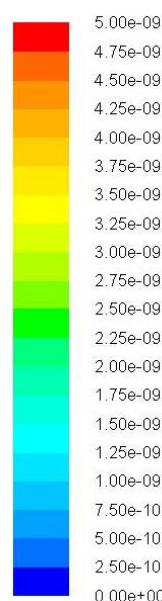
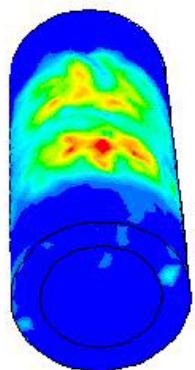
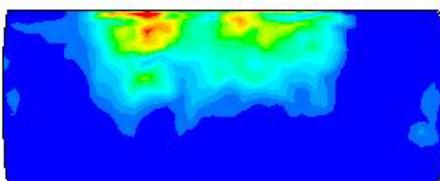
- 점착되어 획득된 회 입자
분율을 파악

Coal	Collie	Coal B
Total coal feeding	10g	10g
Collection efficiency (%)	10.34%	28.59%

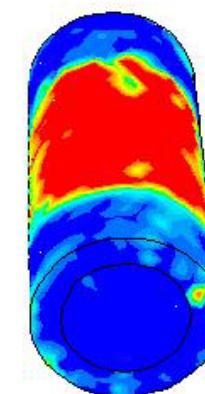
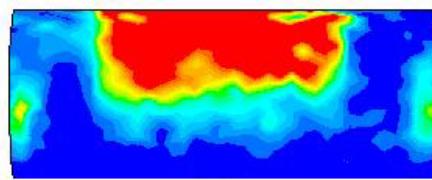
State of the Art in PNU



Collie coal ($T_{cv}=1406K$)



Coal B ($T_{cv}=1325K$)



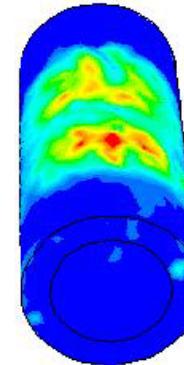
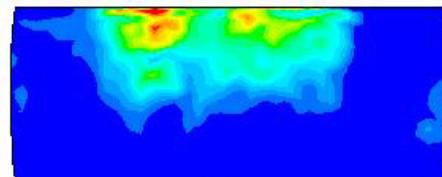
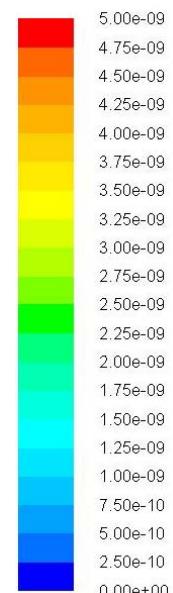
State of the Art in PNU

■ 실험 결과와 비교

Collie

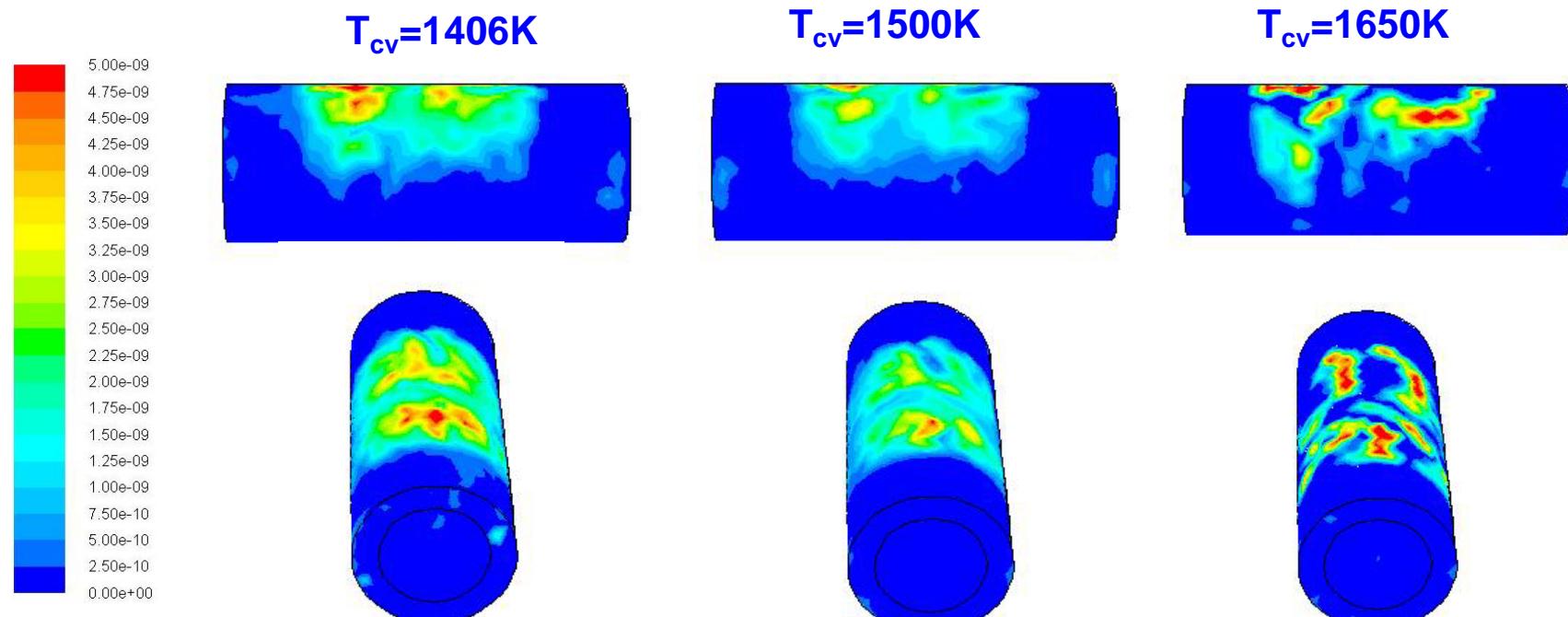


Collie coal ($T_{cv}=1406K$)



State of the Art in PNU

■ T_{cv} 변화에 따른 deposit 예상결과



T_{cv} 에 따른 Deposit량(kg/s) 변화

$T_{cv}(K)$	1406	1500	1650
Deposit rate (kg/s)	2.53×10^{-7}	1.91×10^{-7}	1.78×10^{-7}

Assignment #3 : Slagging& Fouling papers

Key paper 선택 : 2012.10.5 일까지

Presentation 작성 : 15 pages ppt, 2012.10.11 일까지

Uploading : idisk.pusan.ac.kr / update only

ID 111050, PW 123456

Both of paper, presentation.

Top 4 : presentation and A credit

2.1.2.1 Petrographic Analysis

Table 2.4 Macerals of brown and hard coals (Zelkowski 2004)

Brown coal		Hard coal	
Maceral group	Maceral	Maceral group	Maceral
Huminite	Textinite, ulminite attrinite, densinite gelinite, corphuminite	Vitrinite	Telinite, collinite vitrodetrinite
Liptinite	Sporinite, cutinite, resinite, suberinite, alginite, liptodetrinite chlorophyllinite	Exinite	Sporinite, cutinite resinite, alginite liptodetrinite
Inertinite	Fusinite, semifusinite, macrinite, sclerotinite inertodetrinite	Inertinite	Micrinite, macrinite semifusinite, fusinite inertodetrinite

Properties of Maceral

Maceral	H/C	O/C	frac. aromatic C	Density (g/cc)
Liptinite				
Resinite	1.33 - 1.55	0.03 - 0.11		1.01 - 1.15 He
Sporinite	0.92 - 1.13	0.09 - 0.12	0.45 - 0.6	1.15 - 1.25 Aq
Cutinite				
Bituminite	1.3 - 1.5	0.14 - 0.17		
Alginite	1.1 - 1.4	0.10 - 0.07	0.18	1.01 - 1.15 Aq
Vitrinite	0.39 - 0.9	0.10 - 0.33	0.5 - 0.9	
Telocollinite				
Desmocollinite				
Inertinite				
Semifusinite	0.5 - 0.64	0.14 - 0.13		1.28 - 1.50 He
Fusinite	~0.5	~0.13		1.40 - 1.60 He
Micrinite				
Macrinite				
Inertodetrinite				

Origin of Coal

In the view of
Petrographic composition

Origin plants and the extent of their decomposition at the 1st stage of coal formation

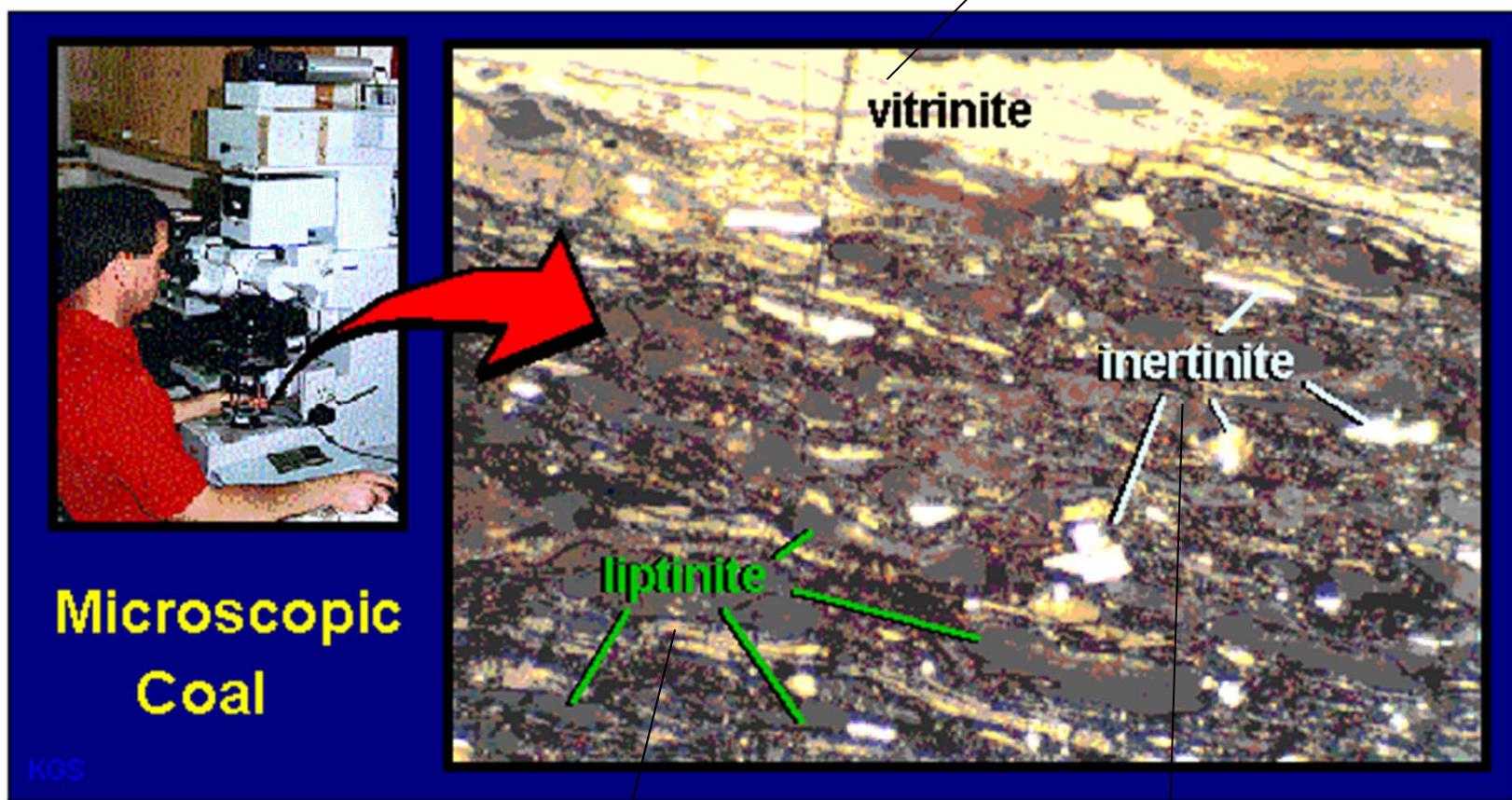
Difference in Petrographic composition

- Macerals Analyzed through
1. Transmitted light method
 2. Reflected light method



How does this approach will enhance your understandings on coal and coal combustion?

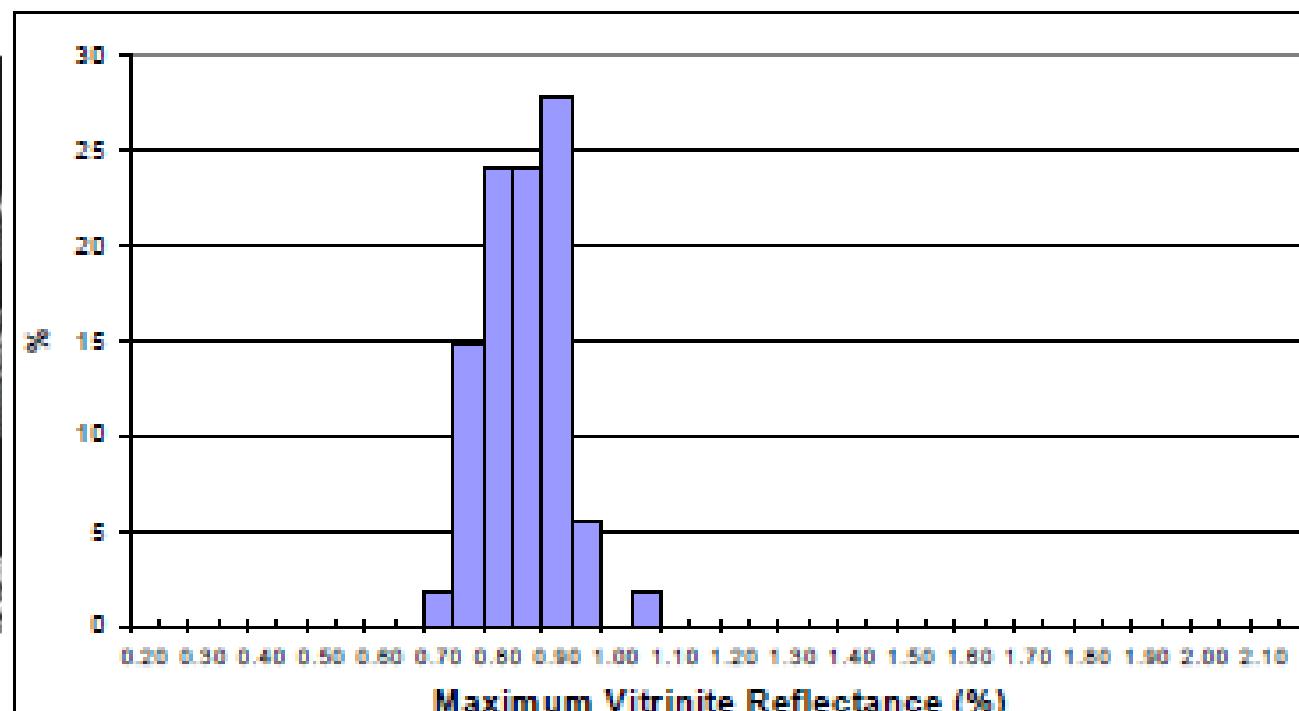
Reflected light method by Microscope



Manual petrography

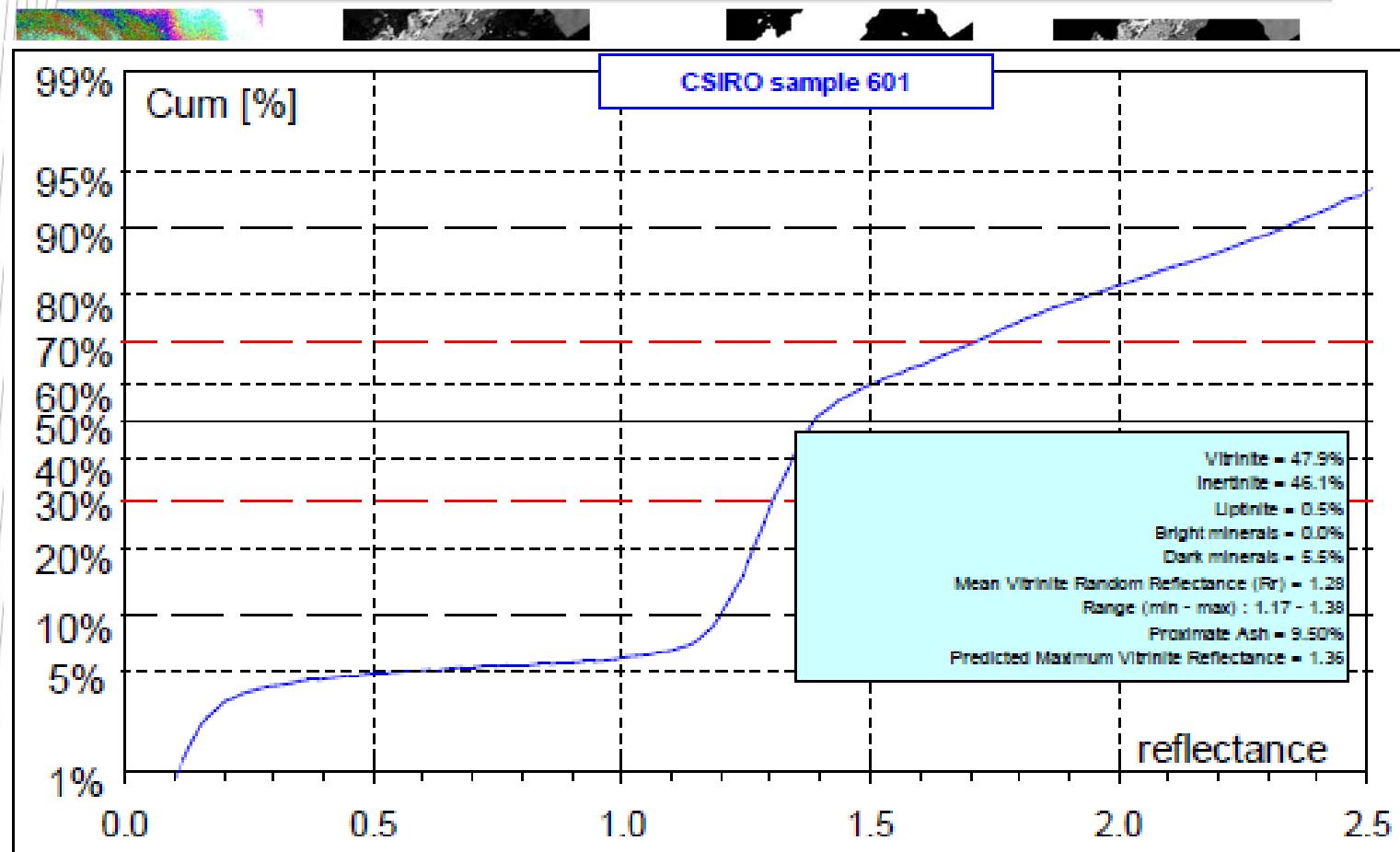
Manual petrography provides composition and rank information. It provides an estimate of mineral abundance but not of mineral maceral associations.

Histogram Data		Range	Frequency %
	Maceral Vol.%	0.50>= <0.55	0.0
Telovitrinite	28.7	0.55>= <0.60	0.0
Detrovitrinite	22.0	0.60>= <0.65	0.0
Gelovitrinite	0.0	0.65>= <0.70	1.9
Sporinite	1.2	0.75>= <0.80	14.8
Other	0.0	0.80>= <0.85	24.1
		0.85>= <0.90	24.4

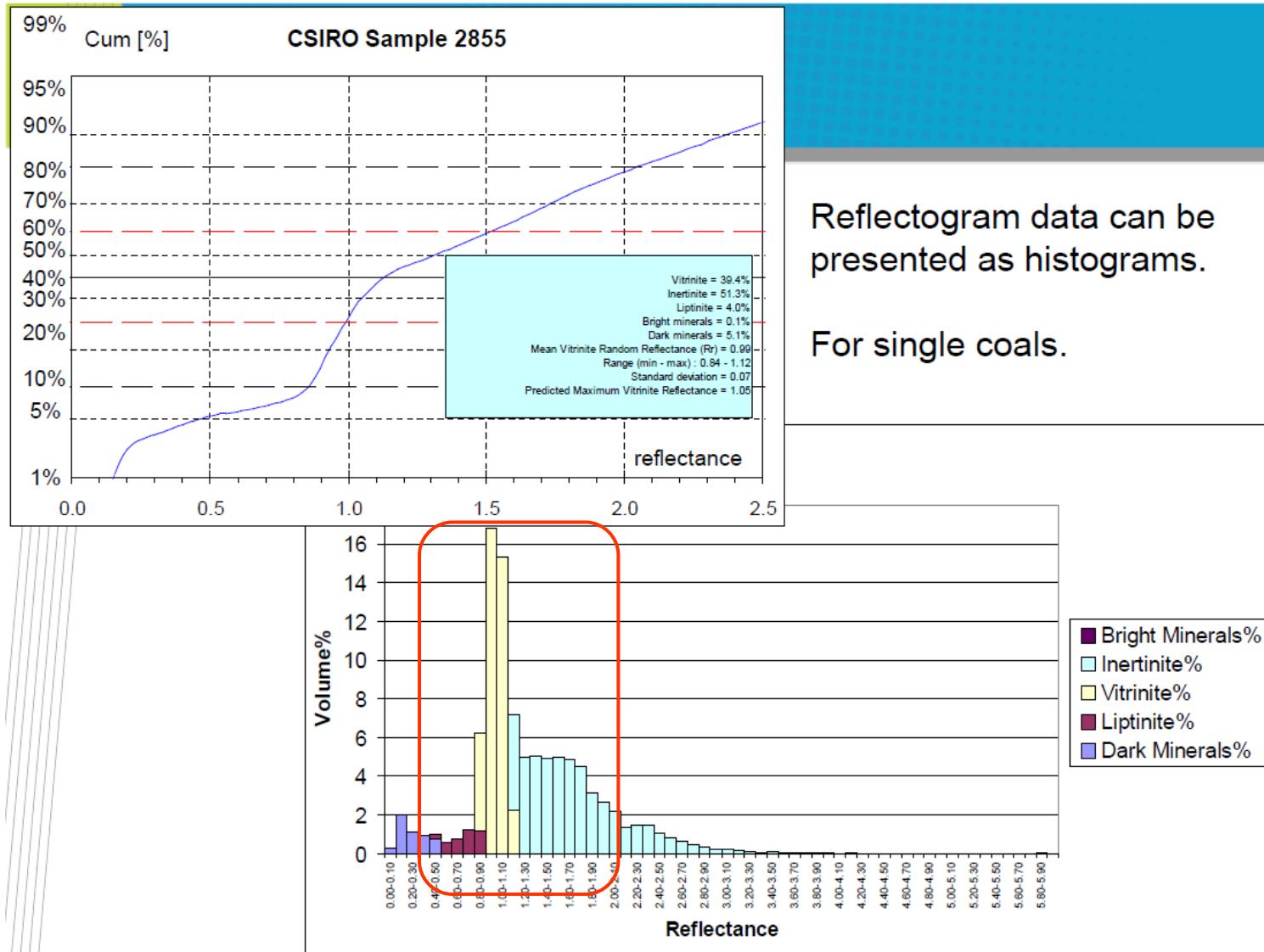


Optical microscopic Image Processing

Optical microscopic Image processing provides a bulk analysis of the sample.



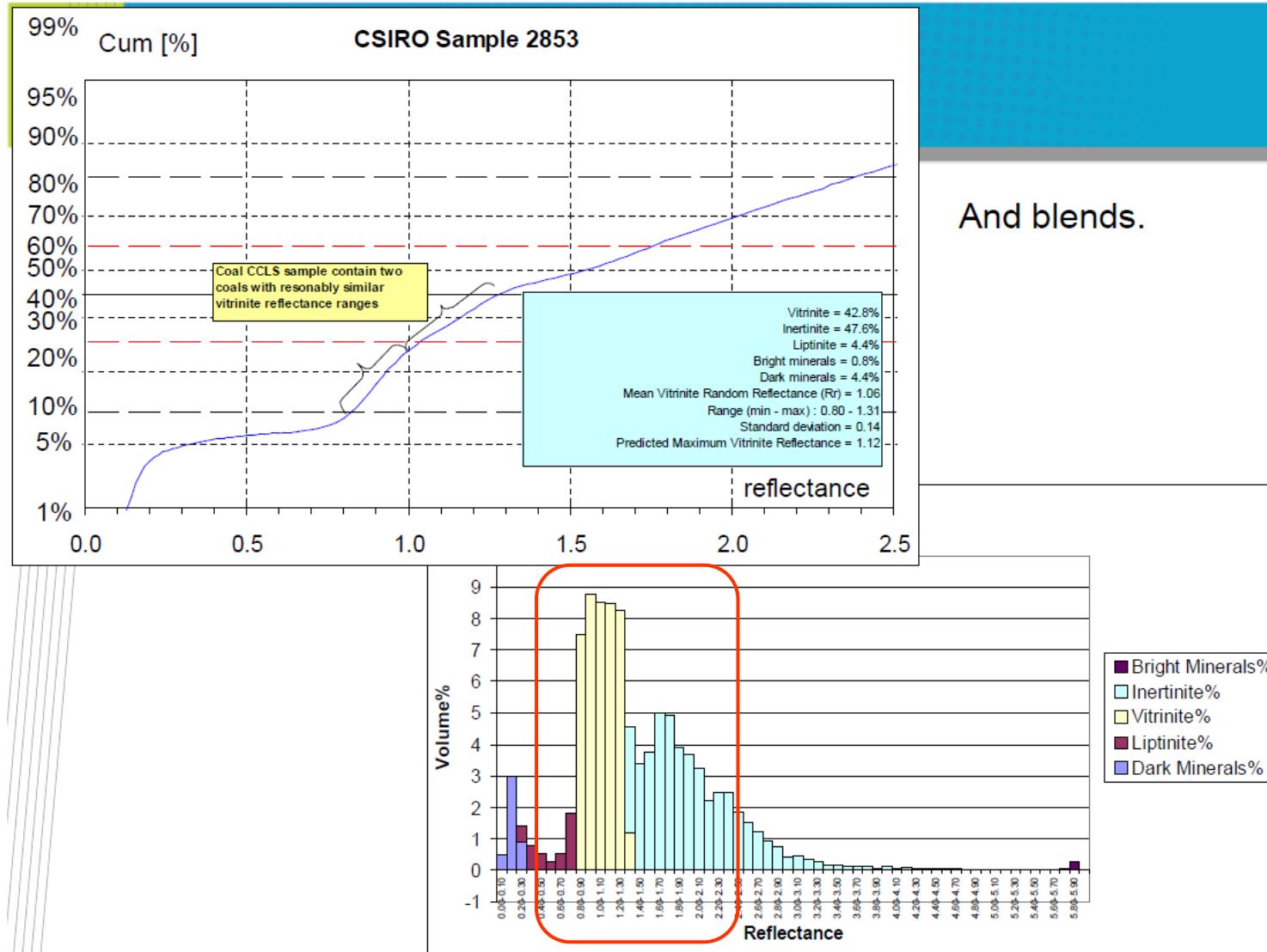
Optical microscopic Image Processing



Reflectogram data can be presented as histograms.

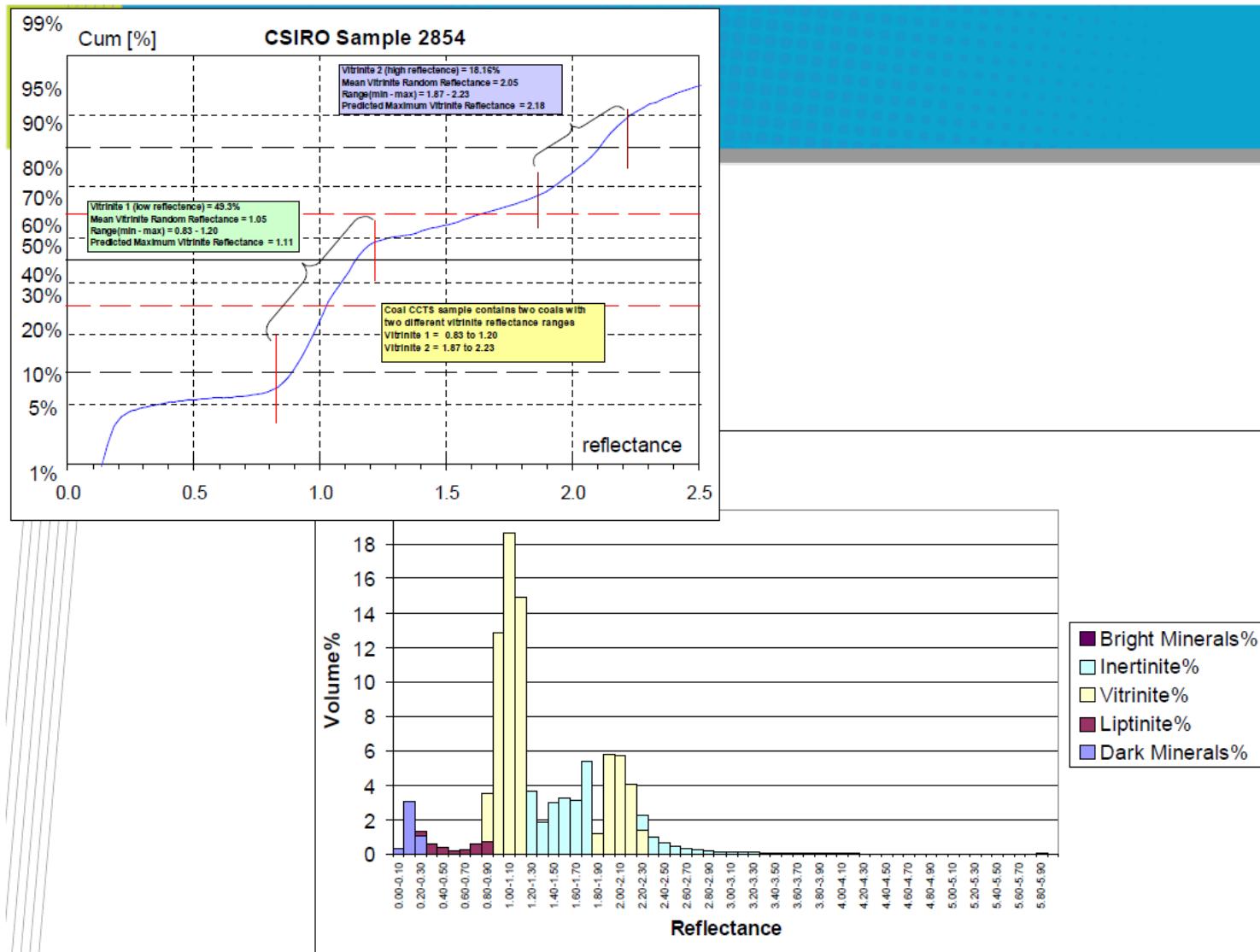
For single coals.

Optical microscopic Image Processing



And blends.

Optical microscopic Image Processing

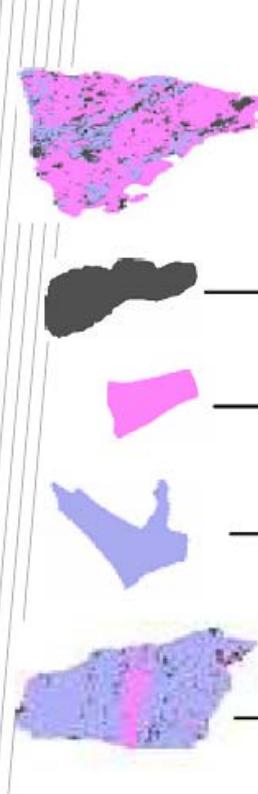


Coal Grain Analysis

- Coal Grain Analysis is an optical technique. The organic phases are identified by their reflectance values.
- It provides size and compositional information on the individual grains in the images.
- The information from the grains can be combined to provide summary whole coal reflectance information (traditional use of imaging for coal petrography applications).

Coal Grain Analysis

Characterisation of daughter particles by Coal Grain Analysis



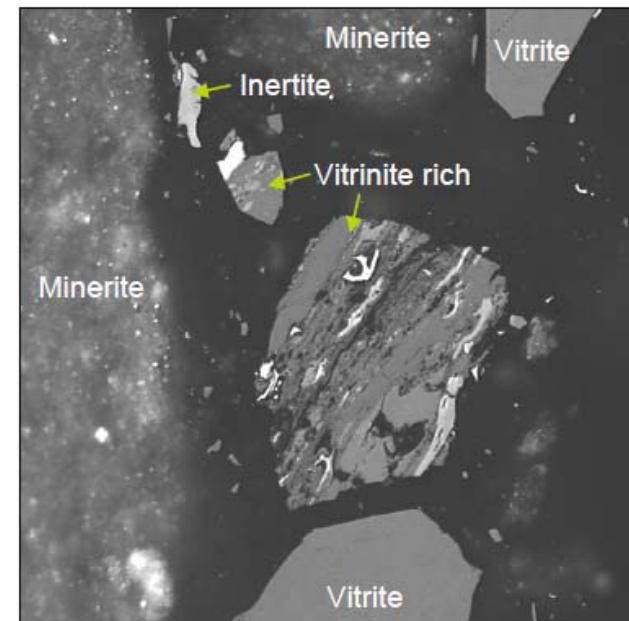
The diagram illustrates the analysis of five different coal grain samples. Each sample is represented by a colored shape (pink, black, pink, blue, and purple) with an arrow pointing to a corresponding row in the data table below. The table provides detailed pixel measurements and grain information for each sample.

Pixel measurements					Volume percent				grain information	
Area	Vitrinite	Inertinite	Dark mins	Bright mins	Vitrinite	Inertinite	Dark mins	Bright mins	density	ash %
249,345	63,972	169,375	15,998	0	25.66	67.93	6.42	0.00	1.368	10.82
3,586	3,586	0	0	0	100.00	0.00	0.00	0.00	1.232	0.29
73,132	46,122	24,530	2,480	0	63.07	33.54	3.39	0.00	1.302	5.96
61,341	48,654	7,260	5,427	0	79.32	11.84	8.85	0.00	1.366	14.59
53,507	41,350	5,063	7,094	0	77.28	9.46	13.26	0.00	1.428	21.13
19,558	0	0	19,558	0	0.00	0.00	100.00	0.00	2.662	69.88
94,148	0	0	94,148	0	0.00	0.00	100.00	0.00	2.662	69.88
245,597	137,115	36,001	72,443	38	55.83	14.66	29.50	0.02	1.664	41.84
251,677	23,415	205,710	22,538	14	9.30	81.74	8.96	0.01	1.413	14.76
5,909	2,852	688	2,362	7	48.27	11.64	39.97	0.12	1.816	52.45
411	0	411	0	0	0.00	100.00	0.00	0.00	1.297	0.29
251,544	2,328	238,036	11,164	16	0.93	94.63	4.44	0.01	1.357	7.67
68,988	68,071	354	563	0	98.67	0.51	0.82	0.00	1.244	1.67
97,794	69,158	19,126	9,510	0	70.72	19.56	9.72	0.00	1.384	15.92
2,847	2,847	0	0	0	100.00	0.00	0.00	0.00	1.232	0.29
251,544	2,328	238,036	11,164	16	0.93	94.63	4.44	0.01	1.357	7.67
68,516	48,401	6,071	14,035	9	70.64	8.86	20.48	0.01	1.531	31.01
3,574	3,534	25	15	0	98.88	0.70	0.42	0.00	1.238	1.00
98,935	27,401	58,045	13,458	31	27.70	58.67	13.60	0.03	1.466	21.67
256,763	0	0	256,763	0	0.00	0.00	100.00	0.00	2.662	69.88
61,422	50,872	9,268	1,282	0	82.82	15.09	2.09	0.00	1.272	3.81
228,103	197,311	28,908	1,884	0	86.50	12.67	0.83	0.00	1.252	1.69
228,754	83,708	102,465	42,581	0	36.59	44.79	18.61	0.00	1.527	28.54
231	223	8	0	0	96.54	3.46	0.00	0.00	1.234	0.29

Coal Grain Analysis

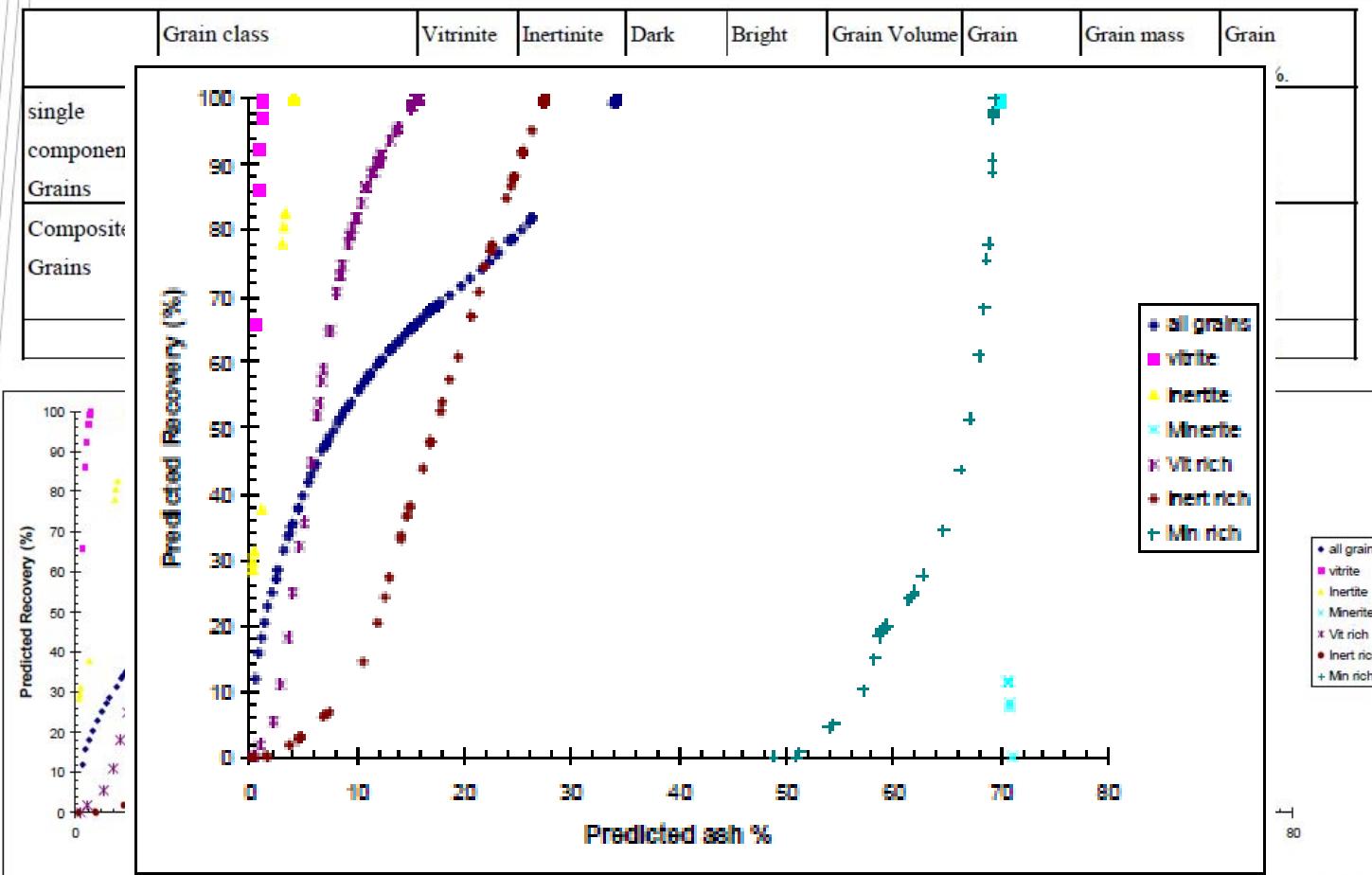
Grains are categorized based on their composition

- Single component grains
 - Vitrite (>95% Vitrinite)
 - Inertite (>95% Inertinite)
 - Liptite (>95% Liptinite)
 - Minerite (>95% Minerals)
- Composite grains
 - Vitrinite rich (V>I, L, Mins)
 - Inertinite rich (I>V, L, Mins)
 - Liptinite rich (L>V, I, Mins)
 - Mineral rich (Mins>V, I, L)



Coal Grain Analysis

Ash data can be generated for the individual grain classes (CSIRO sample 1983).



Thermal and PCI coals

Size Fraction (microns)	sum of grain pixels	% in each fraction
+75	1,012,146	23.0
-75+38	1,279,601	29.0
-38+10	1,436,079	32.6
-10	680,143	15.4
all grains	4,407,969	100.0

Maceral composition (volume basis) of size fractions

Size Fraction	Vitrinite	Inertinite	Liptinite	Dark mineral	Bright mineral
+75	83.2	8.3	2.8	5.4	0.3
-75+38	77.2	14.3	3.6	4.8	0.0
-38+10	66.7	25.7	3.6	3.7	0.3
-10	53.4	40.9	3.1	1.7	0.8
all grains	71.5	20.7	3.3	4.1	0.3

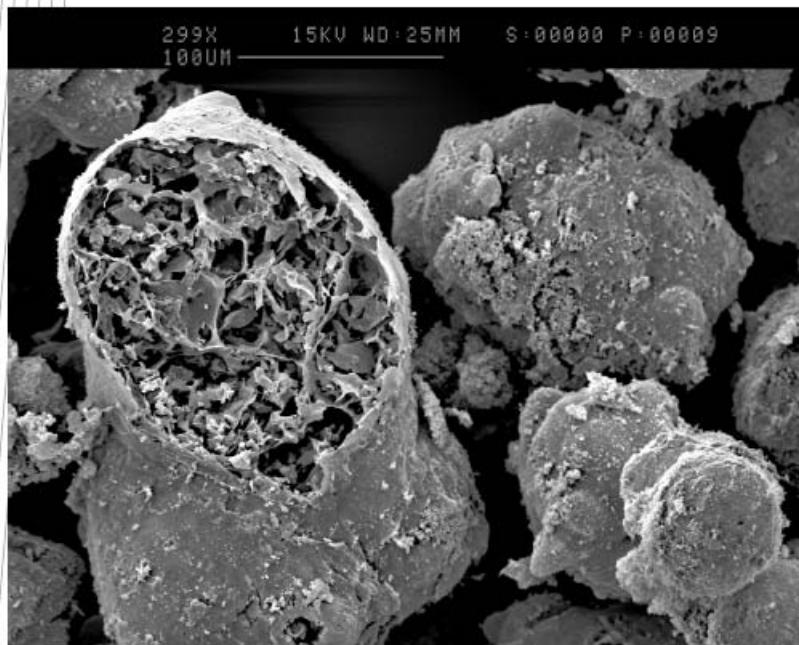
grain composition (mass basis) of size fractions

Size Fraction	Vitrite (>95% vitrinite)	Inertite (>95% inertinite)	Liptite (>95% Liptinite)	Minerite (>95% mins)	Vit rich (V > I, L, mins)	Inert rich (I > V, L, mins)	Liptinite rich (L > V, I, mins)	Min rich (M > V, I, L)
+75	32.8	0.0	0.0	0.0	61.3	5.9	0.0	0.0
-75+38	43.9	2.0	0.0	4.1	38.7	11.3	0.0	0.0
-38+10	31.6	11.9	0.0	1.3	40.0	13.1	0.0	2.1
-10	33.6	28.9	0.0	1.1	21.6	13.0	0.0	1.8
all grains	35.7	8.8	0.0	1.8	42.0	10.9	0.0	0.9

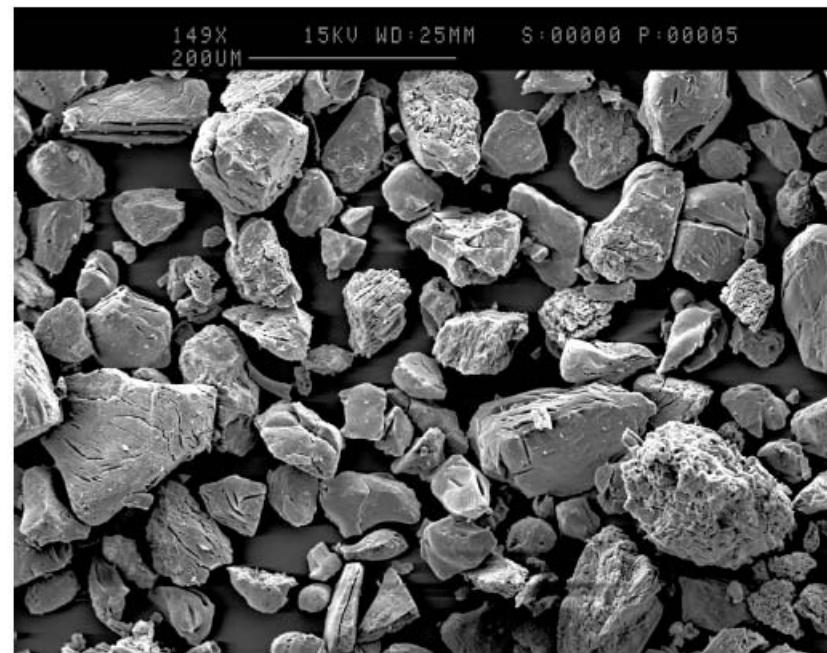
Thermal and PCI coals

Can Char Structures be adequately Modelled?

High vol sub bituminous char



Semi-anthracite char

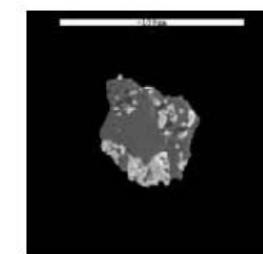
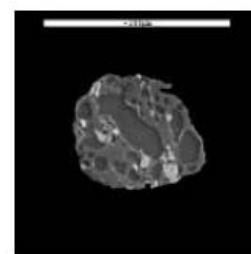
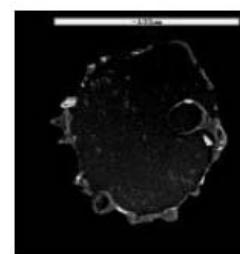


- Need at least some reasoned correlations between coal and char types
- Initial work with empirical correlations

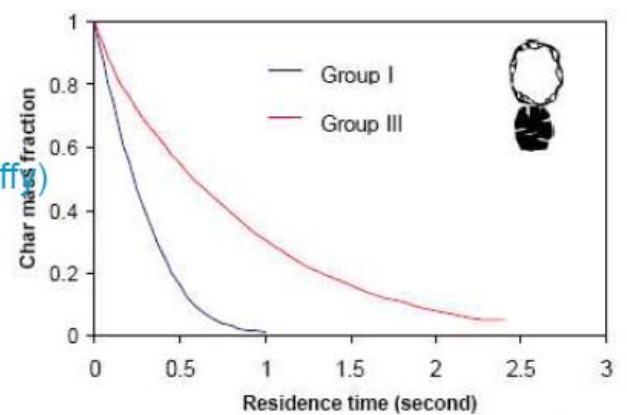
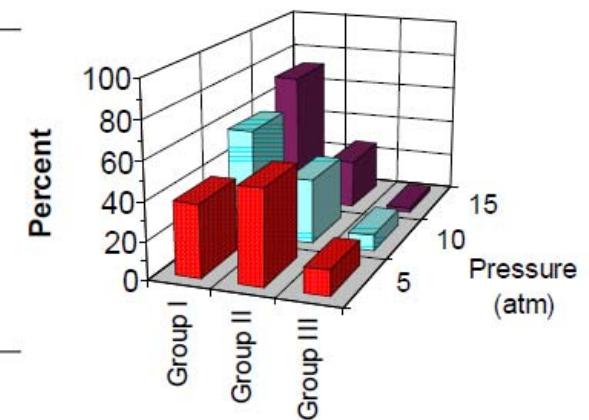
Thermal and PCI coals

Classification of char types (high pressure chars)

Char groups	Group I	Group II	Group III
Two-dimensional schematic representation			
Porosity, %	> 70 %	Variable, 40-70 %	< 40 %
Wall thickness, μm	< 5	> 5	> 5
Shape	Spherical-subspherical	Subspherical	angular
Typical swelling ratio	> 1.3	< 1.0	< 0.9
Typical residual mass ratio	0.1~0.5	0.1~0.5	1.0



- High pressure increases population of Group 1 (fluffy) chars
- Correlated to coal petrography
- Impact on reactivity and modelling



Wu H, Bryant GW, Benfell KE, Wall TF. Energy Fuels 2000; 14:282.



Cocking coals

Coking coal characterisation

- Quantifying the influence that the composition of the individual coal grains in coke oven feed has on coke quality.

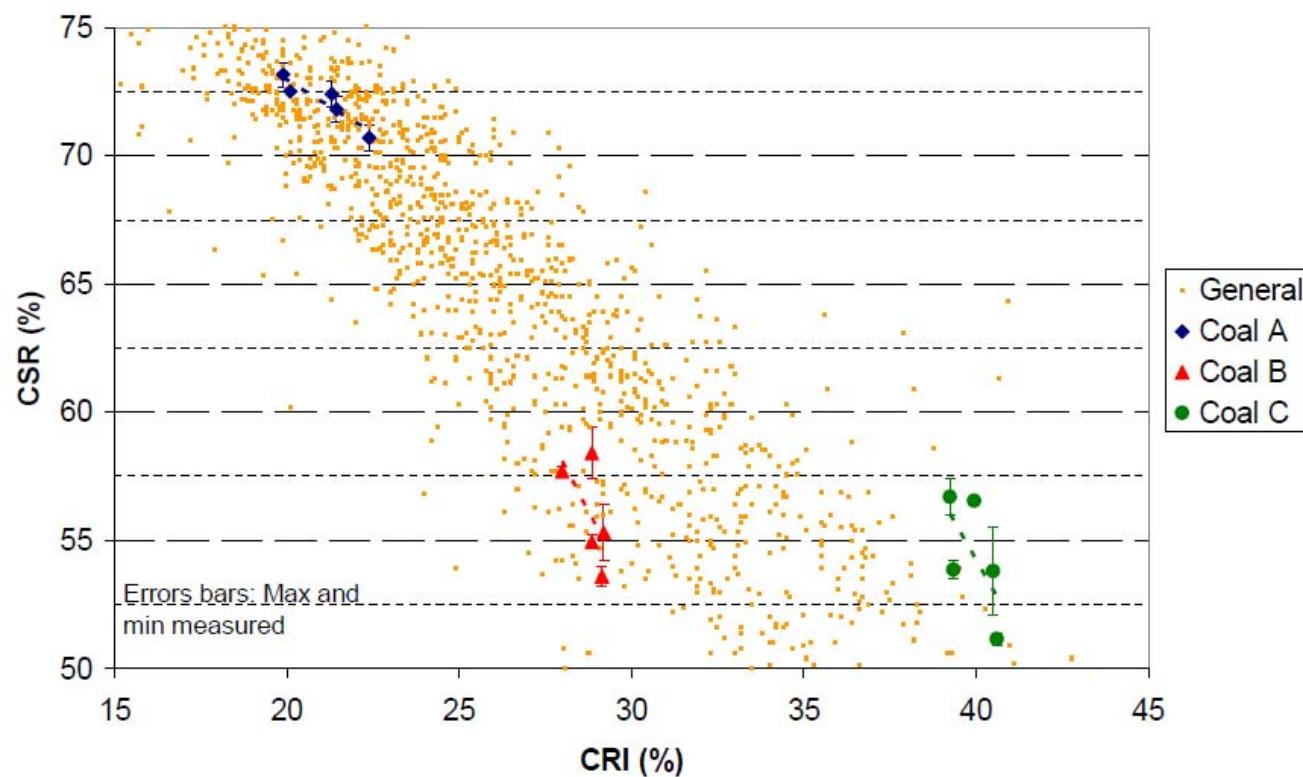
	R1131 VC Vit/VF Inert	R1132 C Vit/F Inert	R1134 N Vit/N Inert	R1135 F Vit/C Inert	R1133 VF Vit/VC Inert
Vitrinite	68.1	65.6	67.7	63.1	68.3
Inertinite	24.6	26.1	23.9	28.1	23.6
Dark Minerals	6.8	7.8	8.0	8.3	7.7
Bright minerals	0.4	0.5	0.4	0.5	0.3
Vitrite	25.3	22.1	22.6	20.2	23.7
Inertite	1.0	0.9	0.6	0.9	0.6
Minerals	0.3	0.2	0.4	0.4	0.2
Vitrinite rich	46.4	47.0	50.2	46.8	50.2
Inertinite rich	23.4	25.3	22.7	27.8	22.2
Mineral rich	3.6	4.4	3.4	4.0	3.0

	Cumulative % passing 1mm				
	R1131 VC Vit/VF Inert	R1132 C Vit/F Inert	R1134 N Vit/N Inert	R1135 F Vit/C Inert	R1133 VF Vit/VC Inert
Vitrinite	55.18	61.64	55.43	59.56	62.63
Inertinite	52.78	51.14	37.10	39.13	43.25
Dark Minerals	57.60	55.08	44.57	44.91	50.69
Bright minerals	49.61	69.87	37.36	58.27	37.81

	Cumulative % passing 1mm				
	R1131 VC Vit/VF Inert	R1132 C Vit/F Inert	R1134 N Vit/N Inert	R1135 F Vit/C Inert	R1133 VF Vit/VC Inert
Vitrite	61.32	71.51	70.03	76.00	79.20
Inertite	78.01	62.79	63.58	73.95	49.68
Minerals	58.66	99.44	68.23	99.97	68.83
Vitrinite rich	50.41	57.01	47.97	52.80	54.17
Inertinite rich	52.14	46.77	34.54	32.67	41.36
Mineral rich	73.73	71.92	48.62	61.33	46.90

Cocking coals

CSR-CRI relations for the cokes prepared in this study compared with the typical relationship observed for cokes prepared in the RCO



Volatile matter of macerals

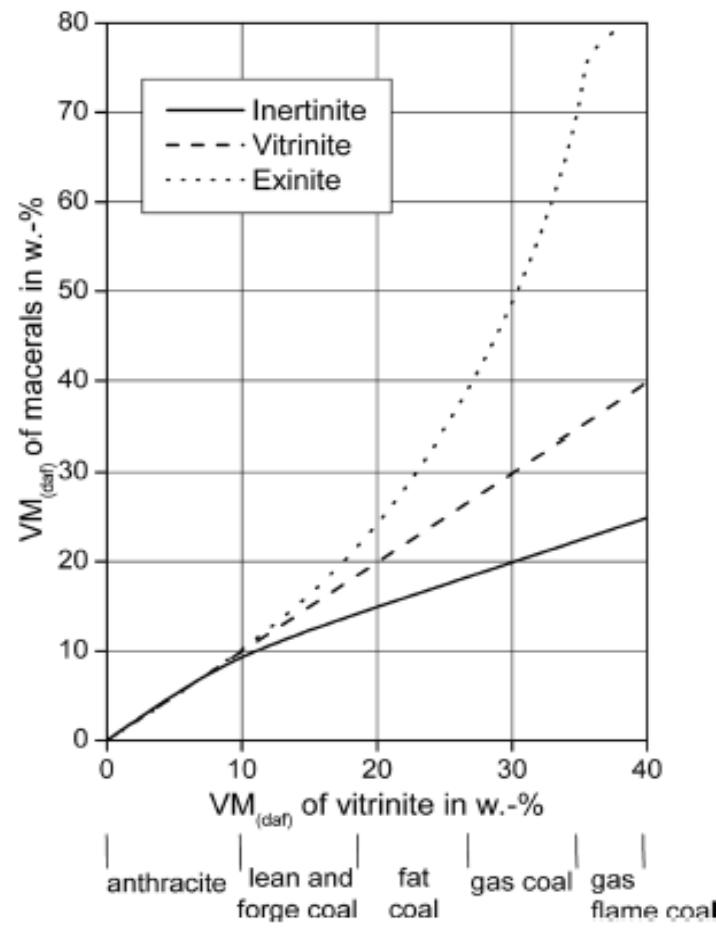


Fig. 2.4 Volatile matter of macerals as a function of the coal type (Ruhrkohle 1987)

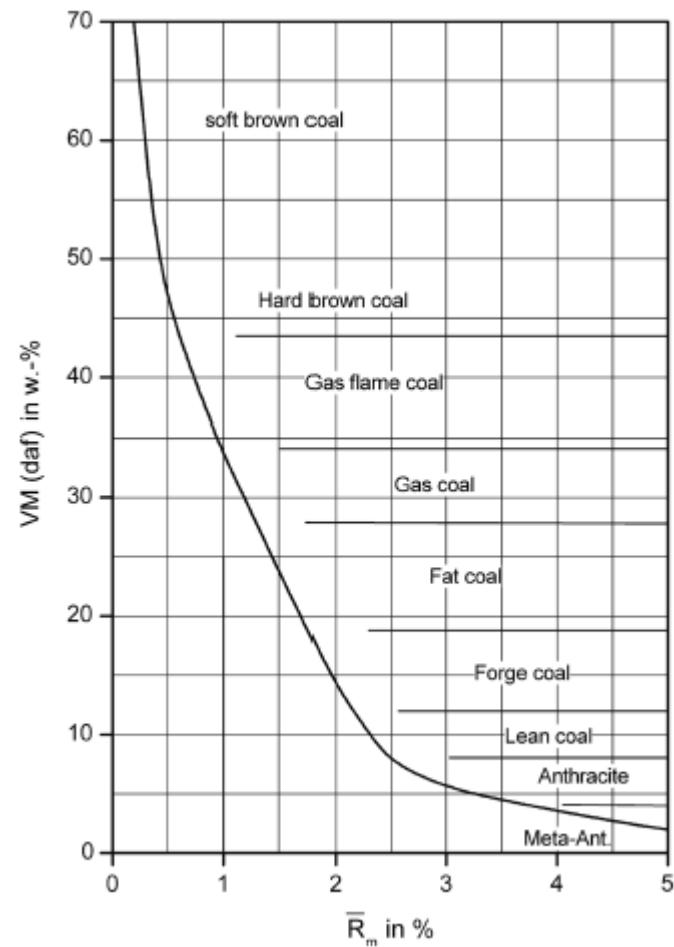
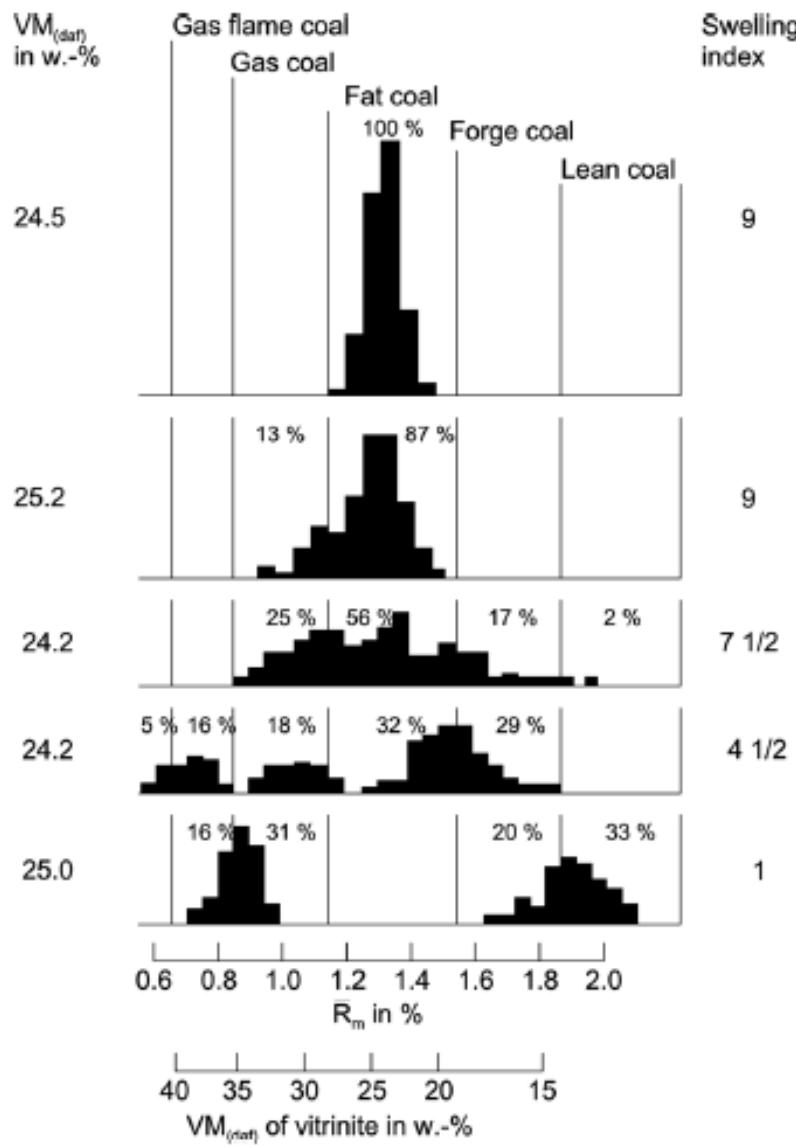


Fig. 2.5 Correlation of the volatile matter content to the reflectance R_m of vitrinite (Ruhrkohle 1987)

Volatile matter of macerals

Fig. 2.6 Reflectance analysis for coals with a similar volatile matter content (Ruhrkohle 1987)



2.1.3 Reserves of Solid Fuels

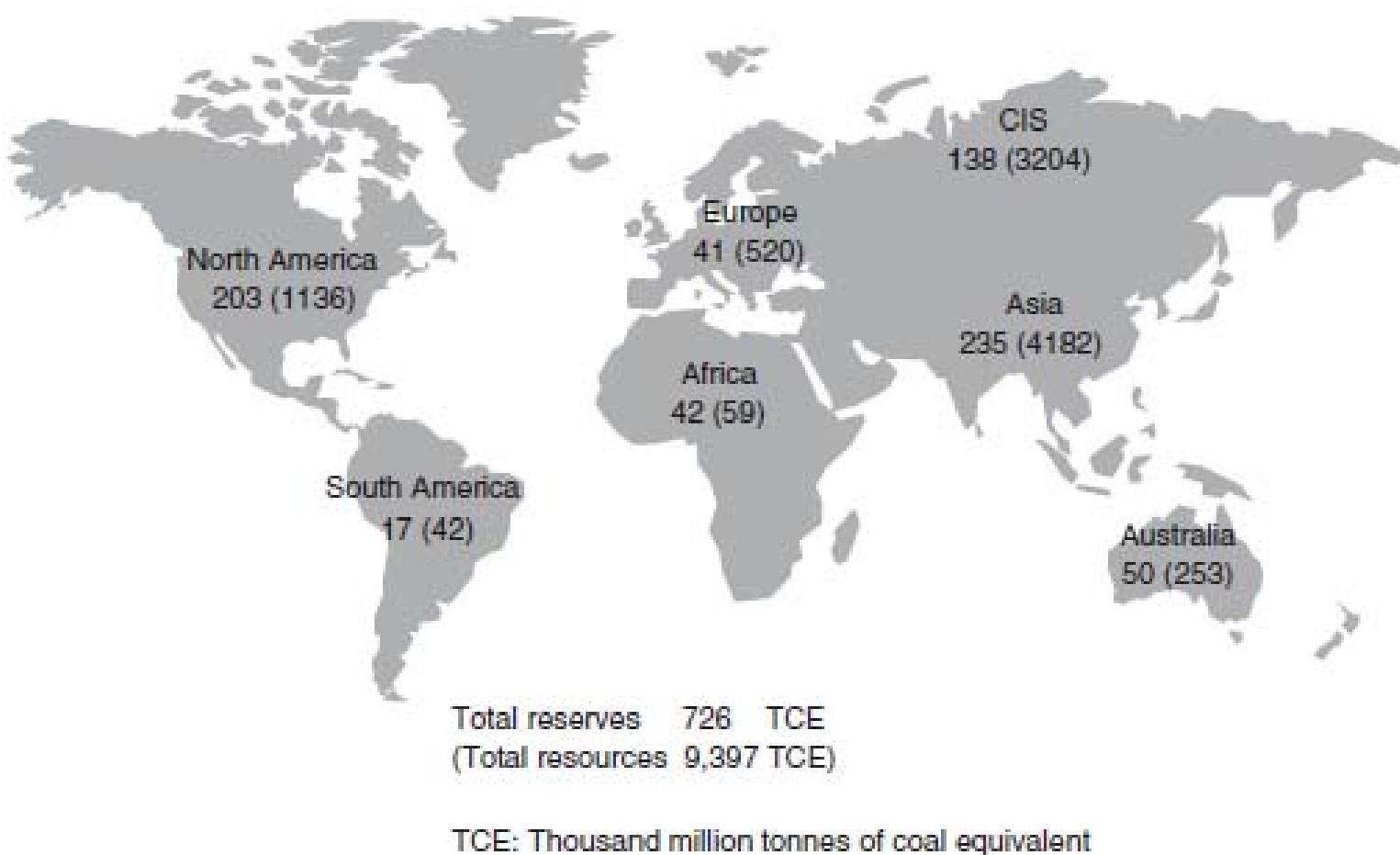


Fig. 2.7 Distribution of coal reserves and resources (data from BMWi 2008)

Coal production and prices

Table 2.5 World coal production and exports (in million tonnes) (IEA 2006)

Production	1980	2004	2015	2030
OECD North America	687	1,080	1,248	1,376
OECD Europe	1,163	834	855	905
OECD Pacific	183	399	450	453
Eastern Europe	842	736	809	707
Africa	93	193	211	248
China	626	1,881	3,006	3,867
India	114	441	636	1,020
Asia, other countries	64	202	295	419
Latin America	18	34	44	63
Total	3,822	5,558	7,328	8,858
Export	172	619	819	975

Fig. 2.8 Coal consumption in the power generation sector and other sectors (data from IEA 2007)

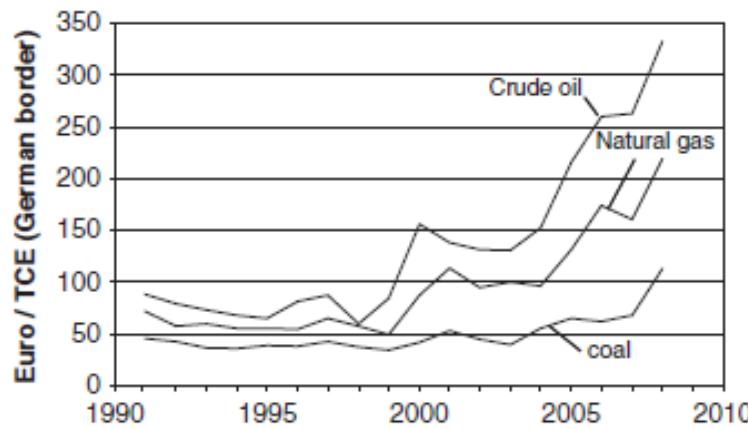
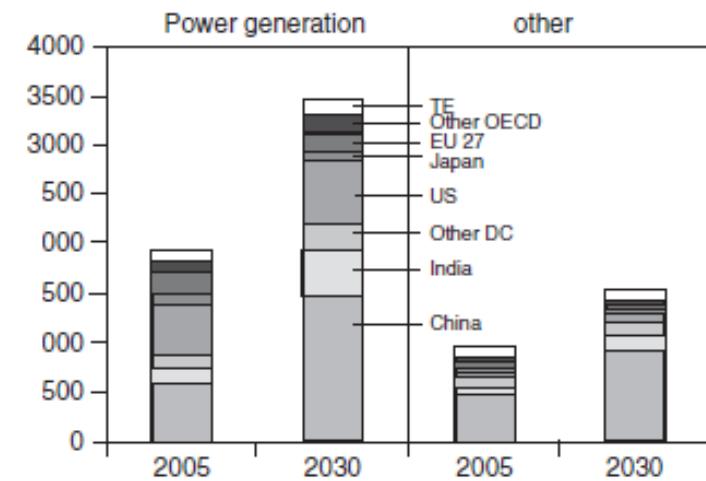


Fig. 2.9 Price trend of hard coal in comparison to oil and natural gas (data from BMWi 2008)

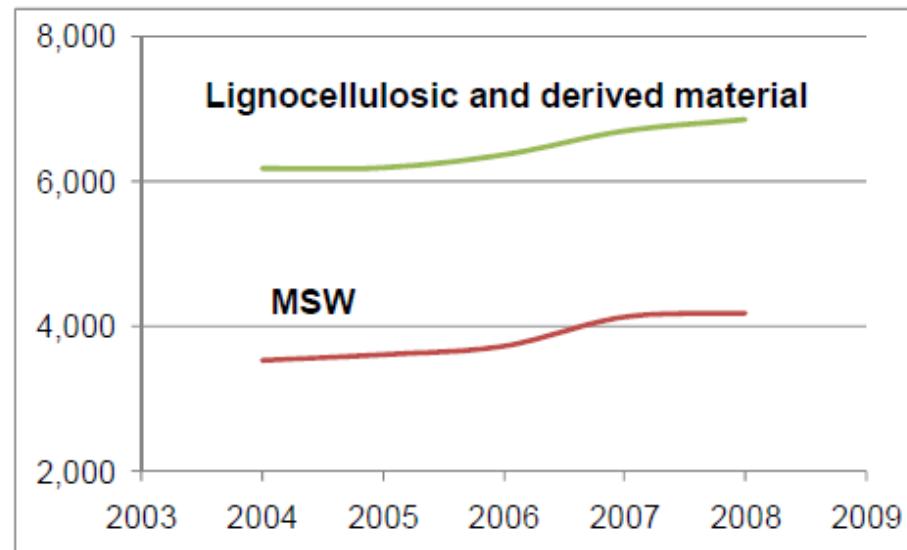


2.2 Renewable Solid Fuels

2.2.1 Potential and Current Utilisation

Renewable Biopower: an example

Electric Net Summer Capacity (Megawatts) in USA



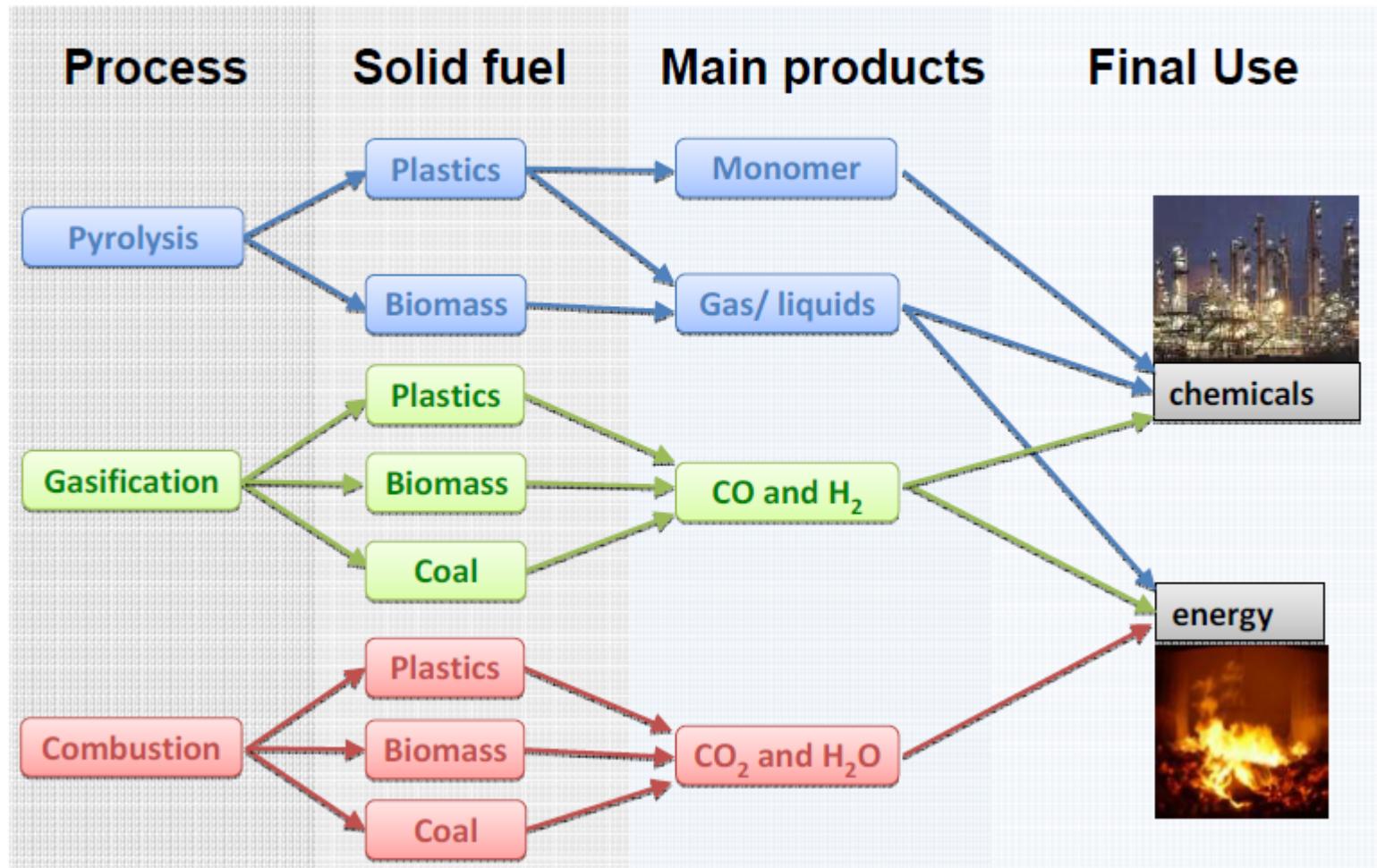
<http://www.eia.doe.gov>

MSW can be directly combusted in waste-to-energy facilities to generate electricity. Because no new fuel sources are used other than the waste that would otherwise be sent to landfills, MSW is often considered a renewable power source.

Source: <http://www.epa.gov>

2.2.1 Potential and Current Utilisation

Processes for solid fuel use



Biomass Status

- 고급탄 확보를 위한 해외탄광 개발 및 저급탄 전처리 기술 개발 추진
- 우드펠렛 확보를 위한 지분출자 및 바이오매스 전용 발전소 건설 추진

발전사 “우드펠릿을 확보하라”

혼소발전으로 RPS 대응하려 해외 지분출자 ‘노크’

조정희 기자 jenie@etnews.com

반전사들이 바이오매스 확보를 위해 해외시장을 두드리고 있다. 신재생에너지 의무합단제(RPS) 시행으로 바이오매스 혼소반전이 늘어날 것으로 예상하면서다.

11일 관련 업계에 따르면 한국남부반전·서부반전·동서반전 등이 석탄과 바이오매스를 섞어 쓰는 혼소반전을 계획하고 문량 확보를 위한 적합지를 물색하고 있다.

확보전이 치열하게 전개될 것으로 예상되는 연료는 우드펠릿이다. 품밥을 재선형한 우드펠릿 특성상 입자가 부드러워 기존 대용량 석탄화학반전소에서도 석탄과

섞여 연료로 바로 사용할 수 있기 때문이다.

반전사들은 전체 연료 3%가량을 섞여 RPS 의무량을 채운다는 구상이다. 500㎿ 반전소는 3%를 섞여 쓰면 15㎿의 신재생에너지 설비를 가능하는 효과를 얻을 수 있다.

반면에 우드칩과 판·코코넛 껌질 등 유동층 보일리를 확보해야 하는 바이오매스는 확보 우선순위를 낮게 보고 있다. 국내에서 유동층 보일리를 사용하는 곳은 동해화력·여수화력으로 제한적인 대다 최근 착공하는 신규 설비에 적용되고 있기 때문이다.

반전사들이 우드펠릿 확보를 위

해 해외시장을 두드리는 것은 국내 문량이 절대적으로 부족하기 때문이다. 국내 모든 석탄화학반전소가 바이오매스를 3% 섞여 반전한다고 가정했을 때 1년간 필요한 연료는 약 320만톤이지만 국내 바이오매스 연간 생산량은 1만톤에 불과하다.

해외 수급처 확보에 선두로 나선 곳은 남부반전이다. 남부반전은 중장기 신재생에너지로 바이오매스를 지목하고 경제성이 우수한 우드펠릿 수급을 위해 캐나다 우드펠릿 개발사업에 지분 출자를 계획하고 있다. 계획대로라면 올해 5월께 지분 계약을 체결한다. 이 연료는 하동화력과 건설 중인

삼척그린파워에 사용할 예정이다. 서부반전은 필리핀 등 동남아시아를 중심으로 수급처를 물색하고 있다. 서부반전은 해외 사업자 지분 인수를 통해 우드펠릿을 현지에서 생산해서 수입하는 방안을构상하고 있다.

동서반전도 당진화력 혼소를 위한 우드펠릿 확보를 준비하고 있고 남동반전은 우드펠릿 수급을 위한 전담팀을 조직했다.

반전사 관계자는 “모든 반전사들이 바이오매스 혼소를 RPS 대응 포트폴리오에 담고 있다”며 “올해를 기점으로 우드펠릿 개발사업자와 다수의 MOU 및 계약사례가 이어질 것”이라고 밝혔다.

Biomass Status

한국경제

**석유 등 화석연료 의존에 한계
바이오연료는 선택 아닌 필수**

2012년 02월 04일 토요일 A30면 종합

이상혁 교수 (80)
서식재료화학과 교수이며, 노스스피스터대학
글리 박사 KSAIST 생명학부 박물학과 특聘교수

자원 풍부하고 재생 가능
매년 지구상에 1700억t 생산
5억t만 연료로 사용

**열대우림 훼손 안하고도
충분한 에너지 생산 가능**

세계 바이오연료 생산 현황

연도	전체 생산량 (백만t)	생산 형태
2009	450	목수수 35.8%, 사탕수수 47.0%, 유채씨 34.0%
2010	450	목수수 35.8%, 사탕수수 47.0%, 유채씨 34.0%
2011	450	목수수 35.8%, 사탕수수 47.0%, 유채씨 34.0%
2012	450	목수수 35.8%, 사탕수수 47.0%, 유채씨 34.0%

국정론 포인트

- 기후 변화와 환경문제 고갈에 대비
- 바이오 적게 드는 바이오연료 연구
- 미생물 발효로 통한 바이오연료 생산 연구
- 이산화탄소 자체에서 바이오연료 생산 연구
- 만방통치학은 아니지만 가야 할 길

□ 자원이 풍부하고 매년 재생 가능한 바이오매스 자원을 활용하는 것은 한정된 화석연료 자원을 이용하는 것에 비해 환경 친화적이며, 지속 가능하고, 현재 우리가 직면한 기후변화 대응에도 기여할 수 있음

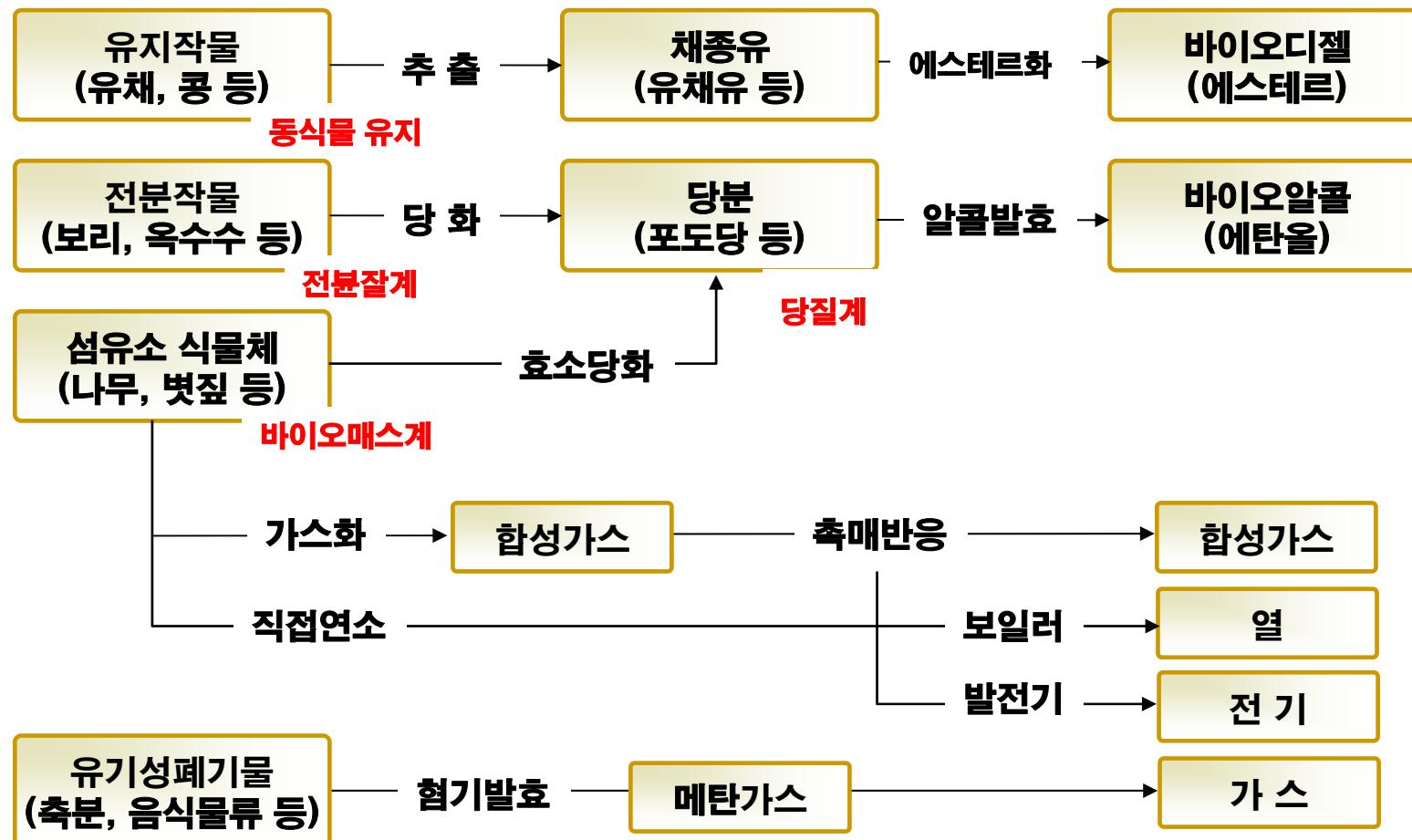
□ 그러나, 바이오연료는 죽음의 연료이며 소위 식량 대 연료 논쟁이 벌어지고 있음. 바이오연료로서 옥수수와 사탕수수가 많이 사용되고 있는데 설탕은 주식이 아니지만 옥수수는 주요 곡물중의 하나임. 아프리카에서 기아로 허덕이는 사람이 2억명 정도

□ 슈가부스터와 같이 설탕을 두배 축적할 수 있는 식물 등의 개발되어 사용될 수 있음

세계 바이오연료 생산 현황 (단위%)



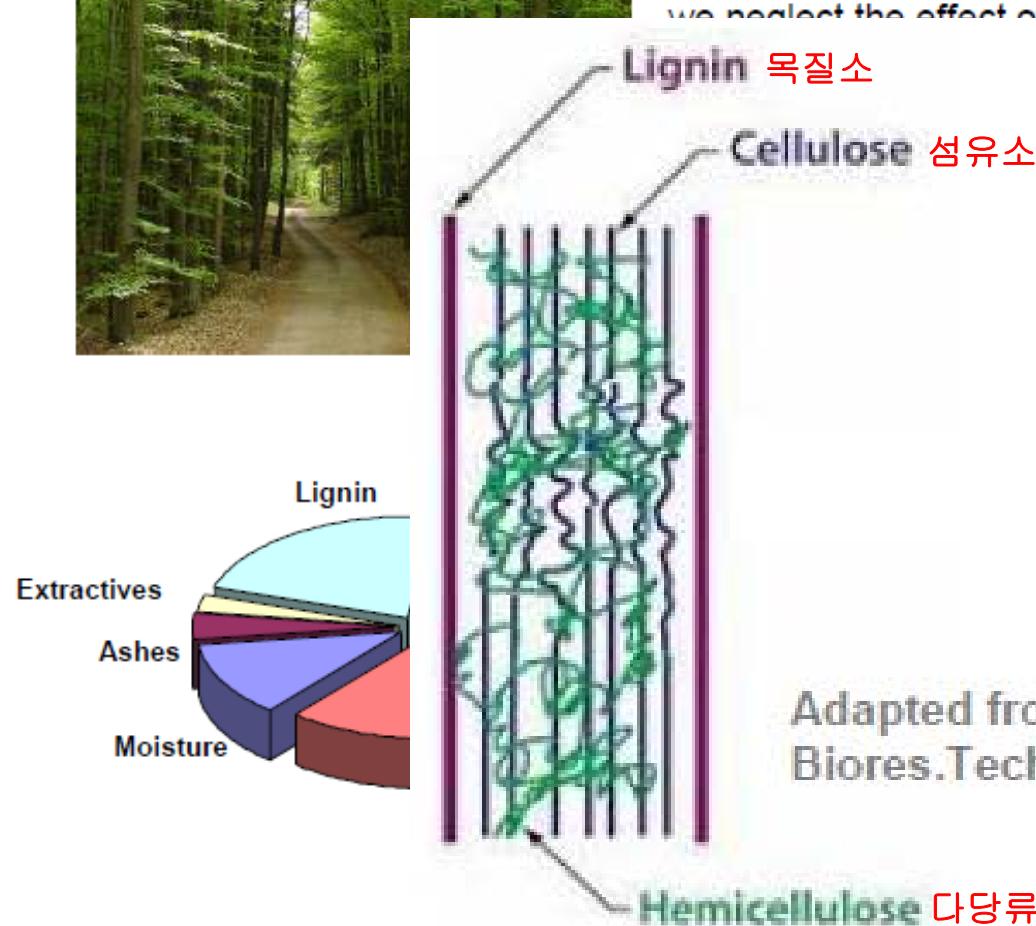
Biomass Production Flow



Biomass – three main components



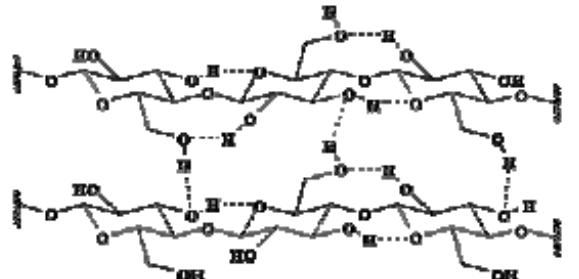
Biomass is all plant and plant-derived material and consists of three main components (~90%): two carbohydrate polymers, cellulose and hemicellulose, and lignin. The extractives are of less importance and we neglect the effect of ashes too.



Adapted from: N. Mosier et al.,
Biore.S.Techn., 96 (2005) 673–686

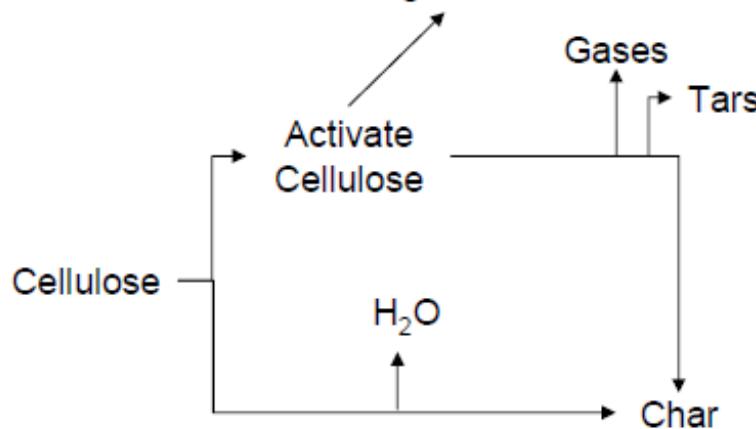
Biomass – three main components; Cellulose

Cellulose mechanism

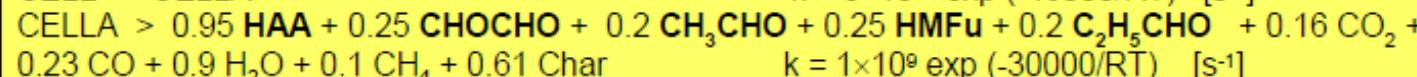


Levoglucosane

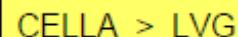
Cellulose is the structural component of the primary cell wall of green plants. Cellulose is a chemically homogeneous linear polymer of up to 10,000 D-glucose molecules with brute formula $(C_6H_{10}O_5)_n$. In principle a modeling approach similar to those of plastics can be applied, but...



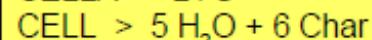
$$k = 8 \times 10^{13} \exp(-46000/RT) \text{ [s}^{-1}\text{]}$$



$$k = 1 \times 10^9 \exp(-30000/RT) \text{ [s}^{-1}\text{]}$$



$$k = 4 \times T \exp(-10000/RT) \text{ [s}^{-1}\text{]}$$

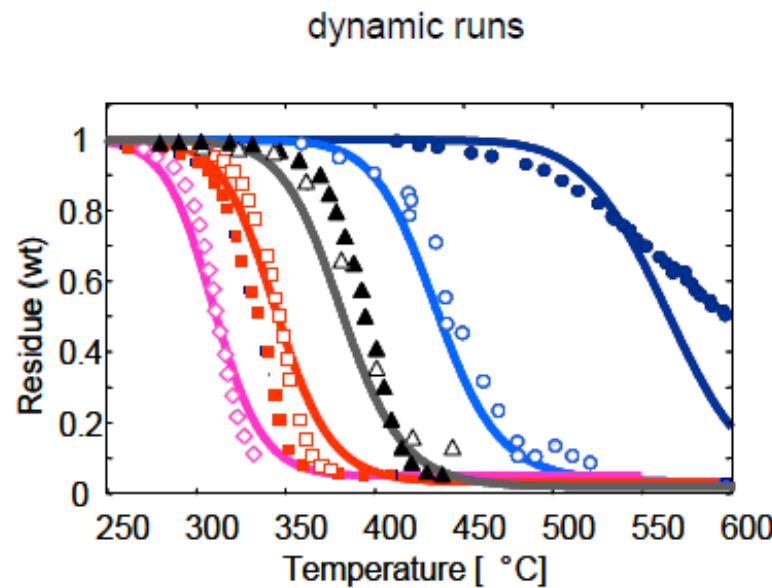


$$k = 8 \times 10^7 \exp(-32000/RT) \text{ [s}^{-1}\text{]}$$

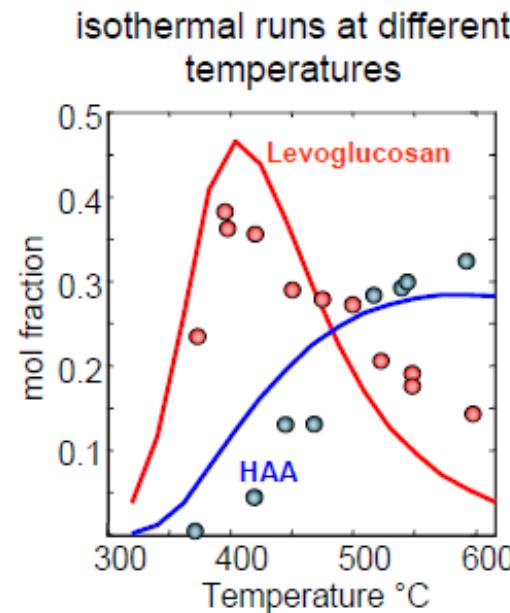
E. Ranzi et al., *Energy Fuels*, 2008, 22 (6), 4292-4300

Biomass – Cellulose

Validation example

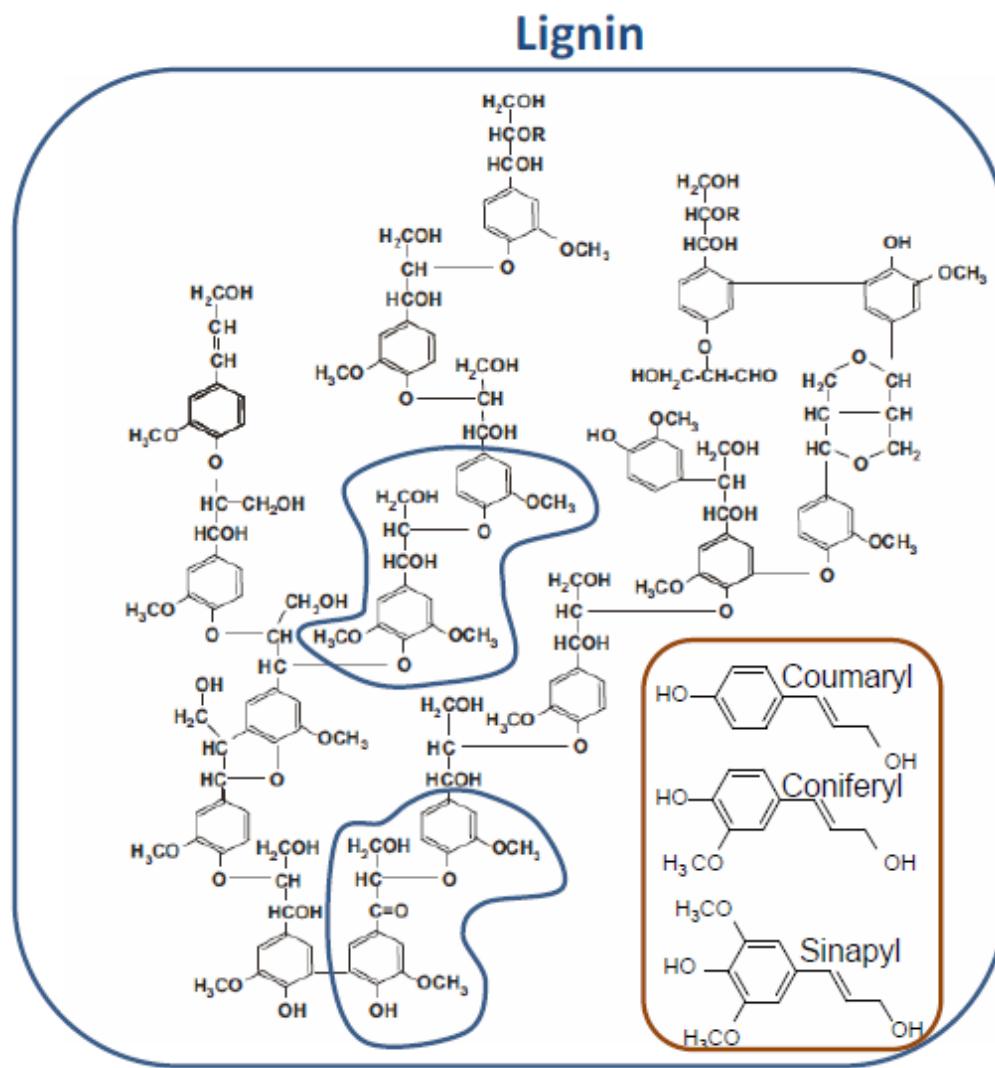


- ◊ 1 °C / min Antal et al, 1998
- 10 °C / min Antal et al, 1995
- 10 °C / min Soares et al 1998
- ▲ 80 °C / min Antal et al, 1998
- △ 80 °C / min Koufopanou et al, 1989
- 1000 °C /min Milosavljevic and Suuberg, 1995
- 1000 °C /s Hajallgol et al, 1982



Data: from Radlein D., Piskorz J. (1991):

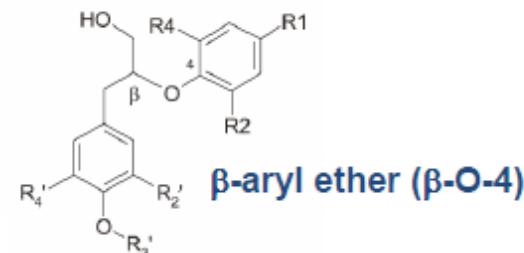
Biomass – three main components; Lignin



Adapted from: Adler E.. Wood Sci Technol 1977;11:169–

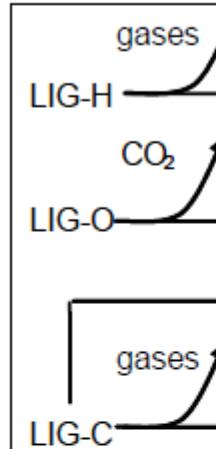
Lignin is a complex chemical macromolecule with a molecular mass in excess of 10,000 u.m.a., whose function is mainly to spaces cellulose and hemicellulose. It is linked to hemicellulose conferring mechanical strength to the plant as a whole.

In the structure there are three monomers, methoxylated to various degrees: *p*-coumaryl, coniferyl, and sinapyl alcohols. The linking between the monomers highlights the presence of some specific groups and in particular of



Biomass – Lignin : Triangular decompositions

Lignin mechanism

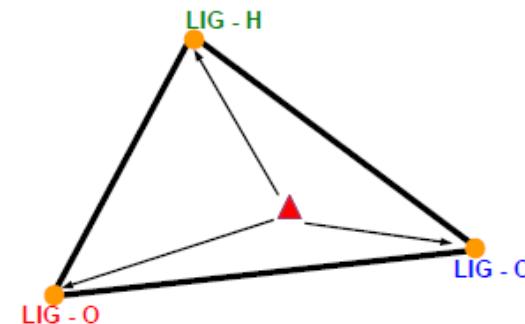
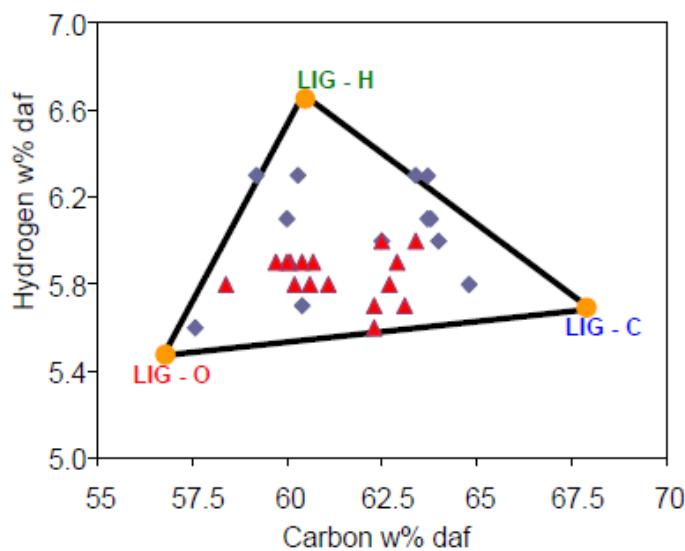


The triangular decomposition



3 pseudocomponents, (a sort of functional groups) whose composition varies according to the relative carbon, hydrogen and oxygen content. LIG-C, LIG-H and LIG-O: where LIG stands for lignin and C-H-O the relative richness in one of the elements. They also account for the differences in the degree of methoxylation

LIG-C > 0.35
 $G(CH_2O) + 5.7$
 LIG-H > LIG_{OH}
 LIG-O > LIG_{OH}
 LIG_{CC} > 0.3 C
 $0.6 C_2H_4 + G(C)$
 LIG_{OH} > LIG +
 $+ 0.1 G(H_2) + 4$
 LIG > $C_{11}H_{12}O$
 LIG > $H_2O + O$
 $0.6 CH_4 + 0.6$

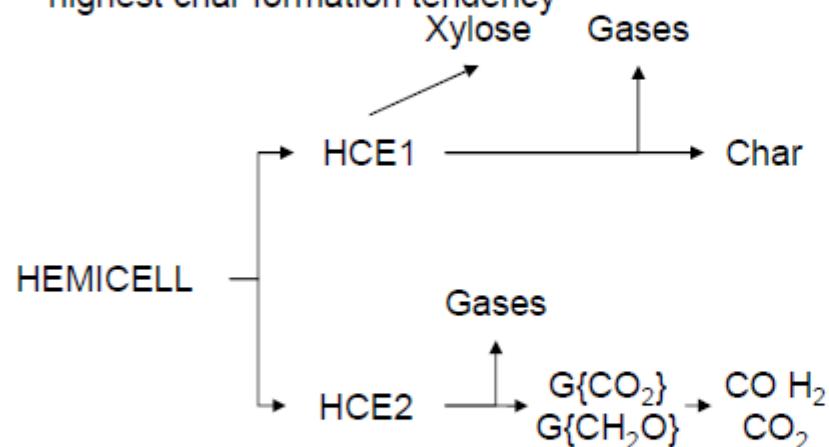


- Jakab et al., J Anal Appl Pyr 1997;40–41:171–86
 - Ullmann's encyclopedia of industrial chemistry, Wiley- VCH, 5th ed

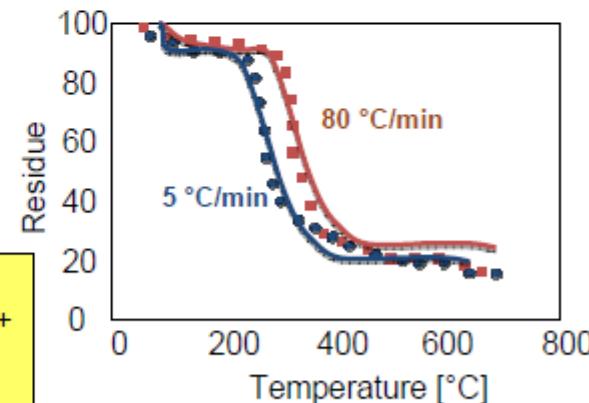
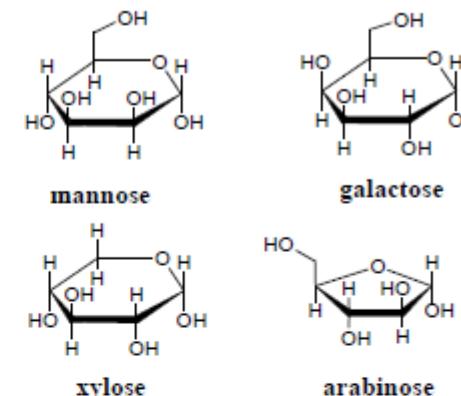
Biomass – Hemicellulose

Hemicellulose mechanism

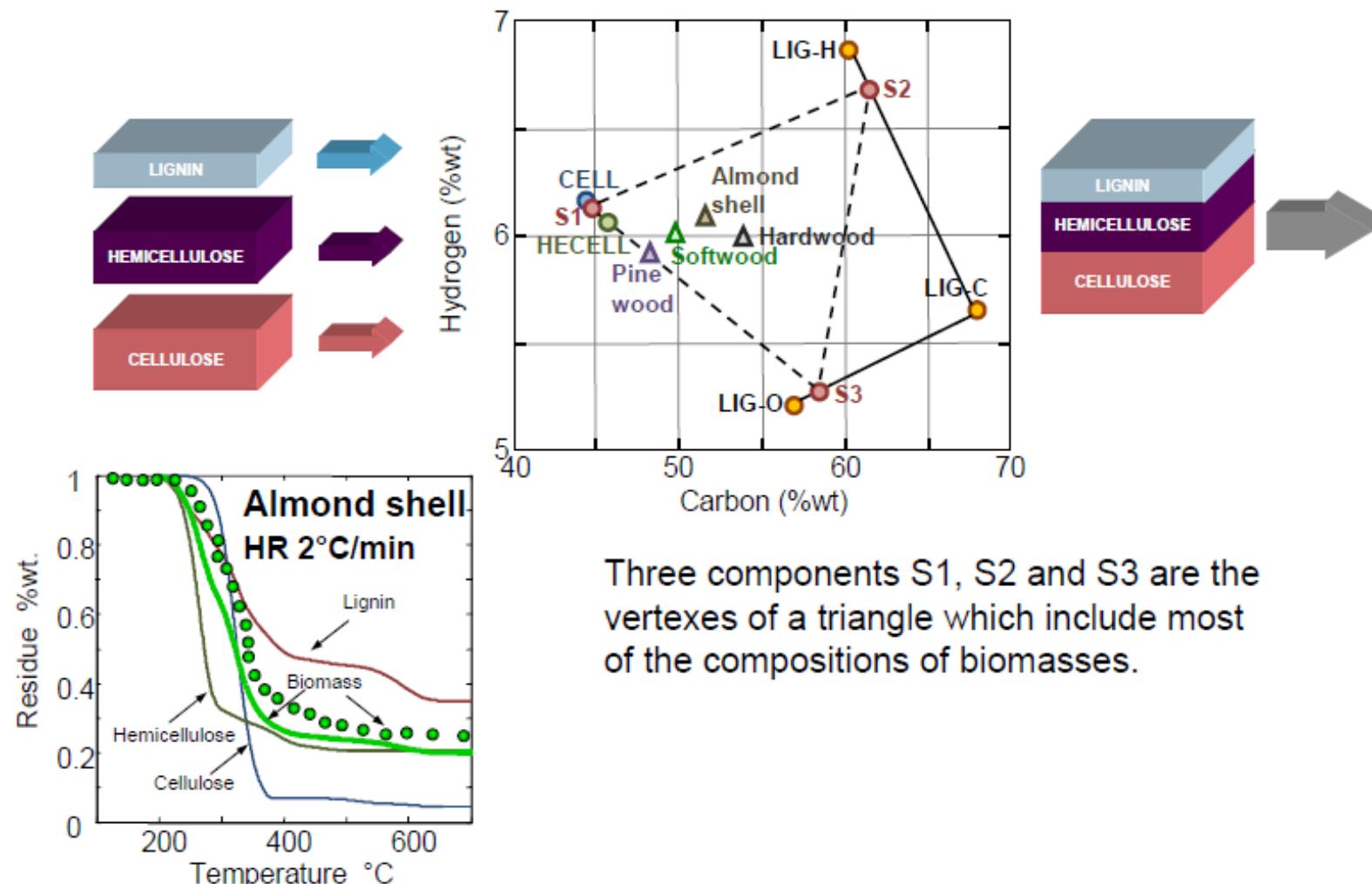
hemicellulose is a complex mixture of many different sugar monomers like xylose, mannose, galactose, arabinose, generally being xylose the most abundant. It has a random, amorphous structure with relative little strength. It is the component in the biomass with the highest char formation tendency



$$\begin{aligned}
 \text{HCE} &> 0.4 \text{ HCE1} + 0.6 \text{ HCE2} \quad k = 1 \times 10^{10} \exp(-31000/RT) \quad [\text{s}^{-1}] \\
 \text{HCE1} &> 0.75 \text{ G(H}_2\text{)} + 0.8 \text{ CO}_2 + 1.4 \text{ CO} + 0.5 \text{ CH}_2\text{O} + 0.25 \text{ CH}_3\text{OH} + \\
 & 0.125 \text{ C}_2\text{H}_5\text{OH} + 0.125 \text{ H}_2\text{O} + 0.625 \text{ CH}_4 + 0.25 \text{ C}_2\text{H}_4 + 0.675 \text{ Char} \\
 & \quad k = 3 \times 10^9 \exp(-27000/RT) \quad [\text{s}^{-1}] \\
 \text{HCE1} &> \text{XYLOSE} \quad k = 3 \times T \exp(-11000/RT) \quad [\text{s}^{-1}] \\
 \text{HCE2} &> 0.2 \text{ CO}_2 + 0.5 \text{ CH}_4 + 0.25 \text{ C}_2\text{H}_4 + 0.8 \text{ G(CO}_2\text{)} + 0.8 \text{ G(CH}_2\text{O)} \\
 & + 0.7 \text{ CH}_2\text{O} + 0.25 \text{ CH}_3\text{OH} + 0.125 \text{ C}_2\text{H}_5\text{OH} + 0.125 \text{ H}_2\text{O} + \text{Char} \\
 & \quad k = 1 \times 10^{10} \exp(-33000/RT) \quad [\text{s}^{-1}]
 \end{aligned}$$

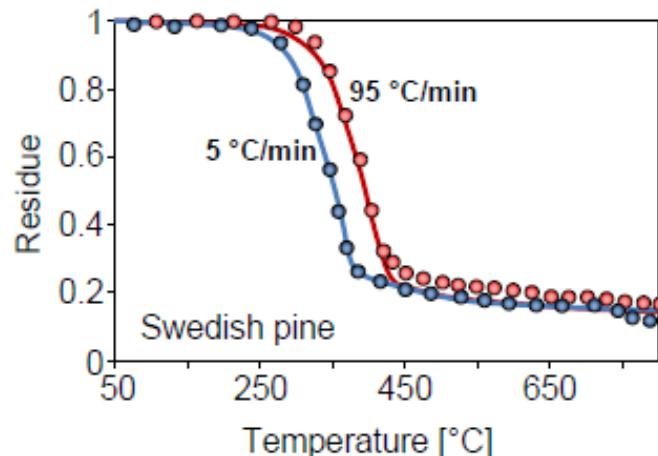


Biomass Volatilization

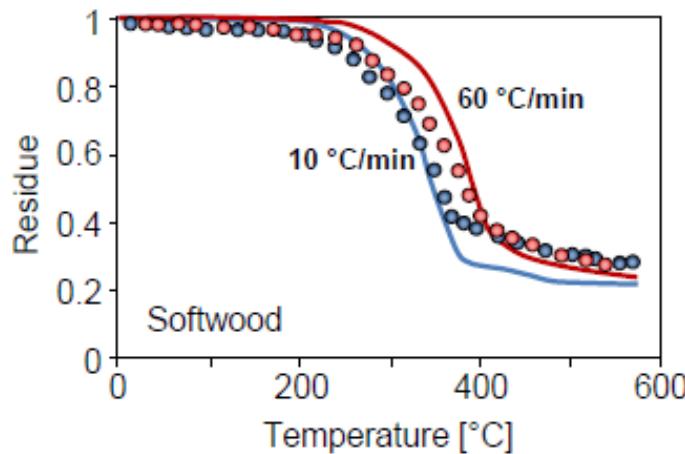
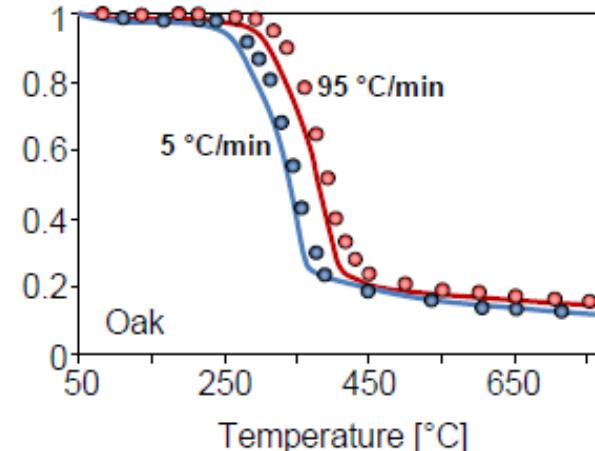


Data from: Caballero J., et al., 1997

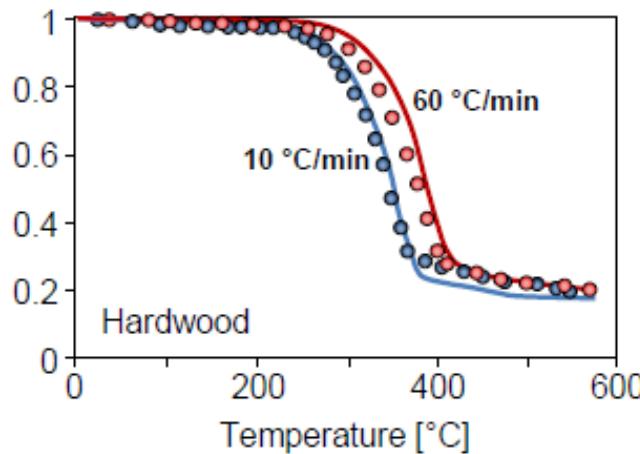
Biomass – Heating rate effect



Data from Sommariva et al., *XXXI Italian Meeting on Combustion*, 2008



Data from Garcia-Pérez et al., *J. Anal. Appl. Pyrol.* 2007



2.2.1.1 Biomass from Farming and Forestry

Table 2.6 Biomass potential and utilisation in Germany (Schneider 2007)

	Potential	Utilisation	Potential/PEC	Utilisation/PEC
	in PJ/yr		Share in %	
Residual forest wood	169	147–165	3.0	1.0–1.1
Small wood	123			
Additional forestry wood	132			
Wood industry residuals	57	51	0.4	0.4
Waste wood	78	62	0.5	0.4
Other woody biomass	10	1	0.1	0
Straw	130	3	0.9	0
Grass, other	48–77	0	0.4–0.6	0
Energy crops	365	0	2.6	0
Total	1,112–1,141	261–279	7.8–8.0	1.8–2.0

PEC: Primary energy consumption

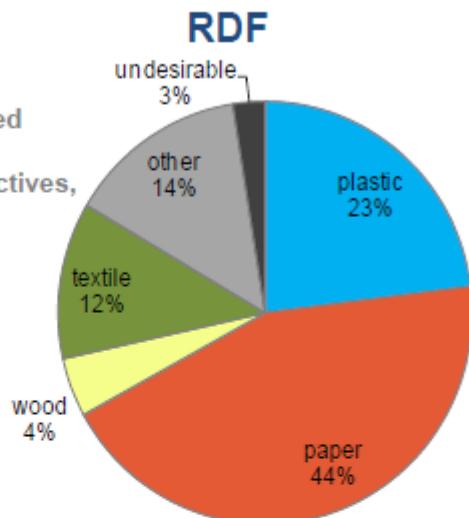
Table 2.7 Biomass potential, current utilisation and share of PEC in different regions of the world
(Schneider 2007; Van Loo 2008; Kaltschmitt et al. 2009)

	North America	Latin America	Asia	Africa	Europe	Middle East	Former SU	Total
Potential [EJ/a]								
Wood	12.8	5.9	7.7	5.4	4.0	0.4	5.4	41.6
Herbaceous biomass	2.2	1.7	9.9	0.9	1.6	0.2	0.7	17.2
Dung	0.8	1.8	2.7	1.2	0.7	0.1	0.3	7.6
Biogas	(0.3)	(0.6)	(0.9)	(0.4)	(0.3)	(0.0)	(0.1)	(2.6)
Energy crops	4.1	12.1	1.1	13.9	2.6	0.0	3.6	37.4
Total	19.9	21.5	21.4	21.4	8.9	0.7	10.0	103.8
Current utilisation [EJ/a]								
Trad. biomass		1.2	22.5	9.7				33.4
Modern biomass	4.1	2.4	3.6	2.3	3.4		0.7	16.8
Total	4.1	3.6	26.1	12	3.4	0	0.7	50.2
PEC [EJ/a]	120.4	21.8	154.8	25	78.9	19.5	46.5	473
Utilisation/ PEC [%]	3	17	17	48	4	0	2	10.6
Potential/ PEC [%]	17	98	14	86	11	1	22	22

2.2.1.2 Wastes

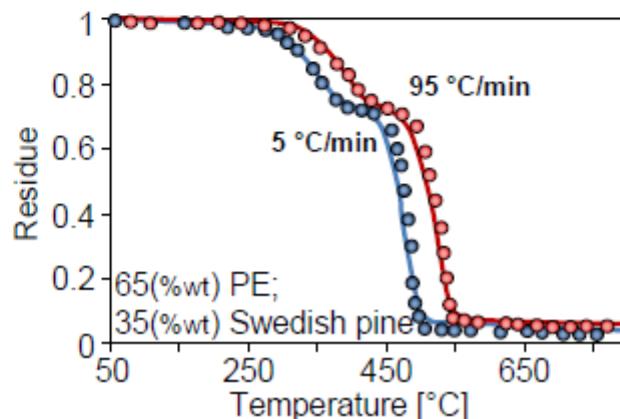
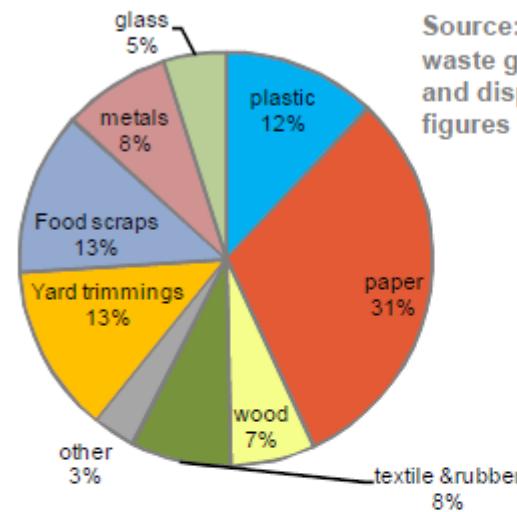
Waste volatilization

Source: European Commission. Refused derived fuel, current practice and perspectives, 2003



MSW

Source: EPA Municipal Solid waste generation, recycling and disposal in USA: facts and figures for 2008



Data from Sommariva et al., XXXI Italian Meeting on Combustion, 2008

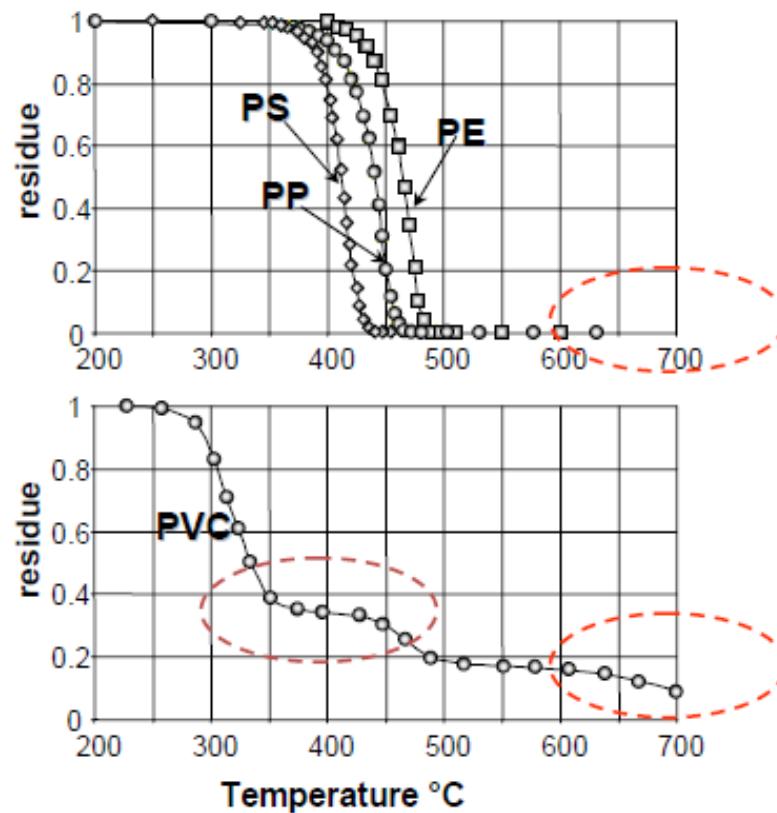
2.2.1.2 Wastes : plastic and others

Main plastic degradation paths

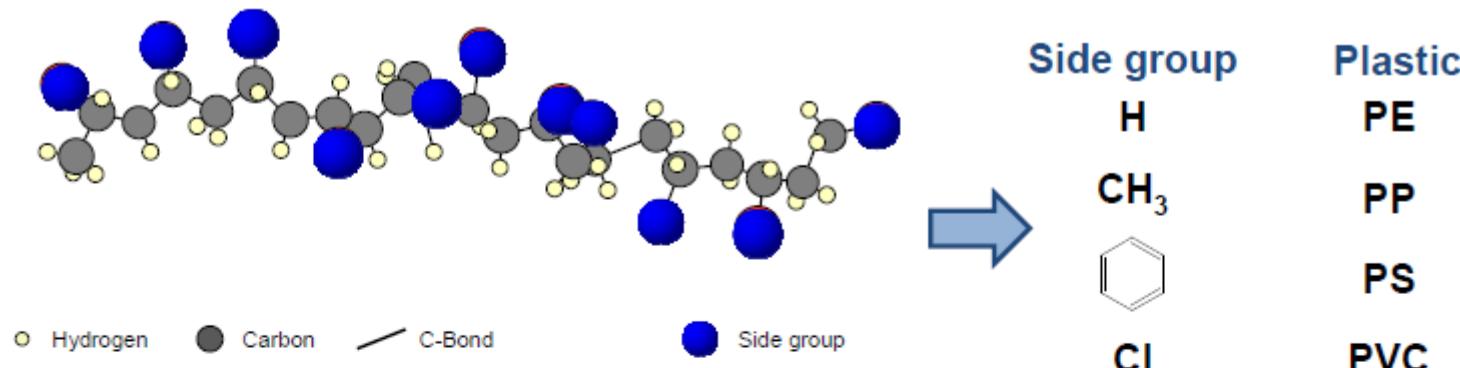
Typical result of thermogravimetric analysis (TGA) of main plastics

➤ Plastics

- Polyethylene (PE)
- Polypropylene (PP)
- Polystyrene (PS)
- Polyvinylchloride (PVC)
- Mixtures



2.2.1.2 Wastes : plastic structure



Plastic volatilization is a liquid phase radical mechanism with two main pathways:

Depolymerization — Molecular weight decrease

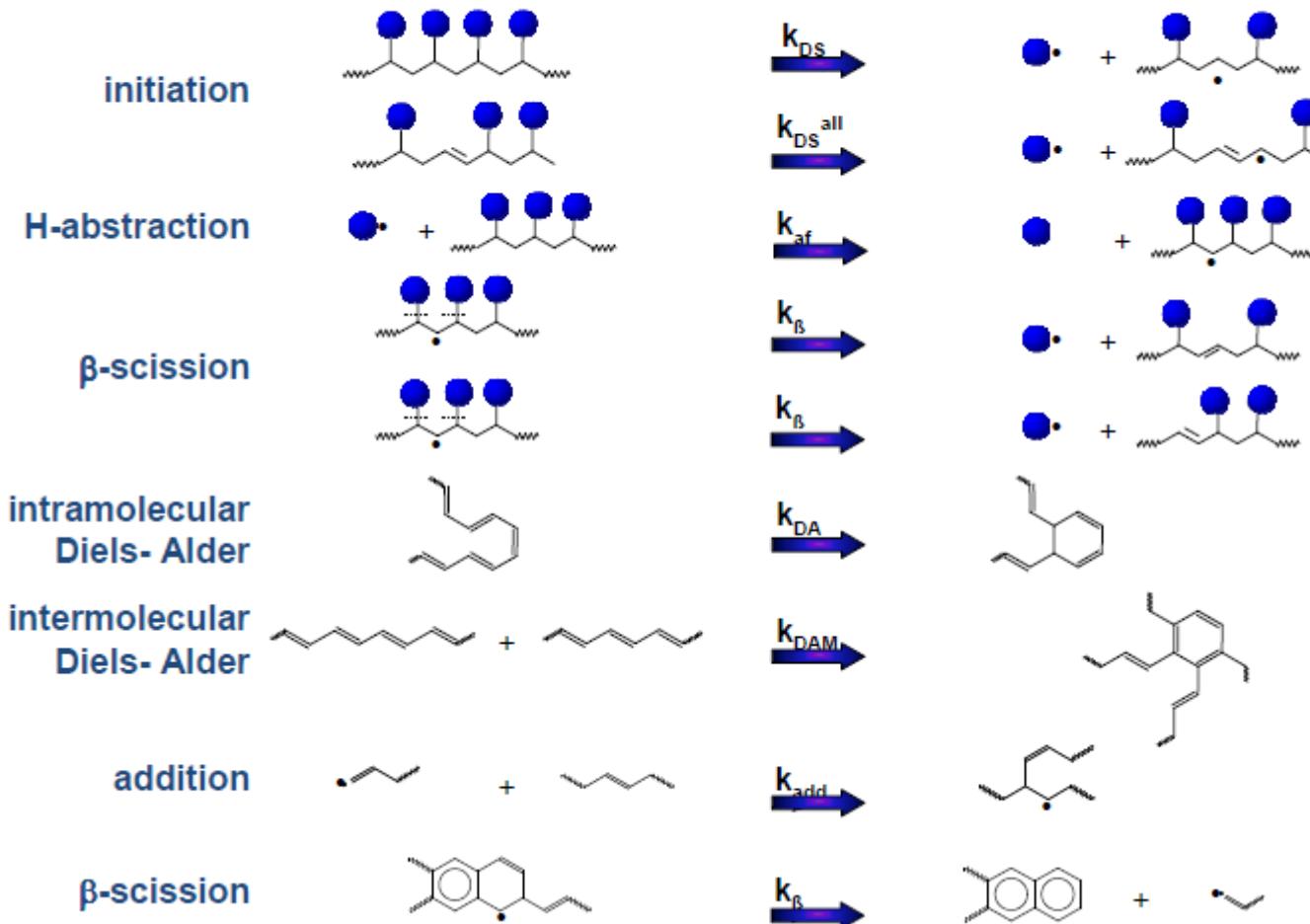
- Light gas products (monomer, dimers, ...)
- Tars and Waxes (oligomers and polymer chain fragments)

Side Group — Elimination

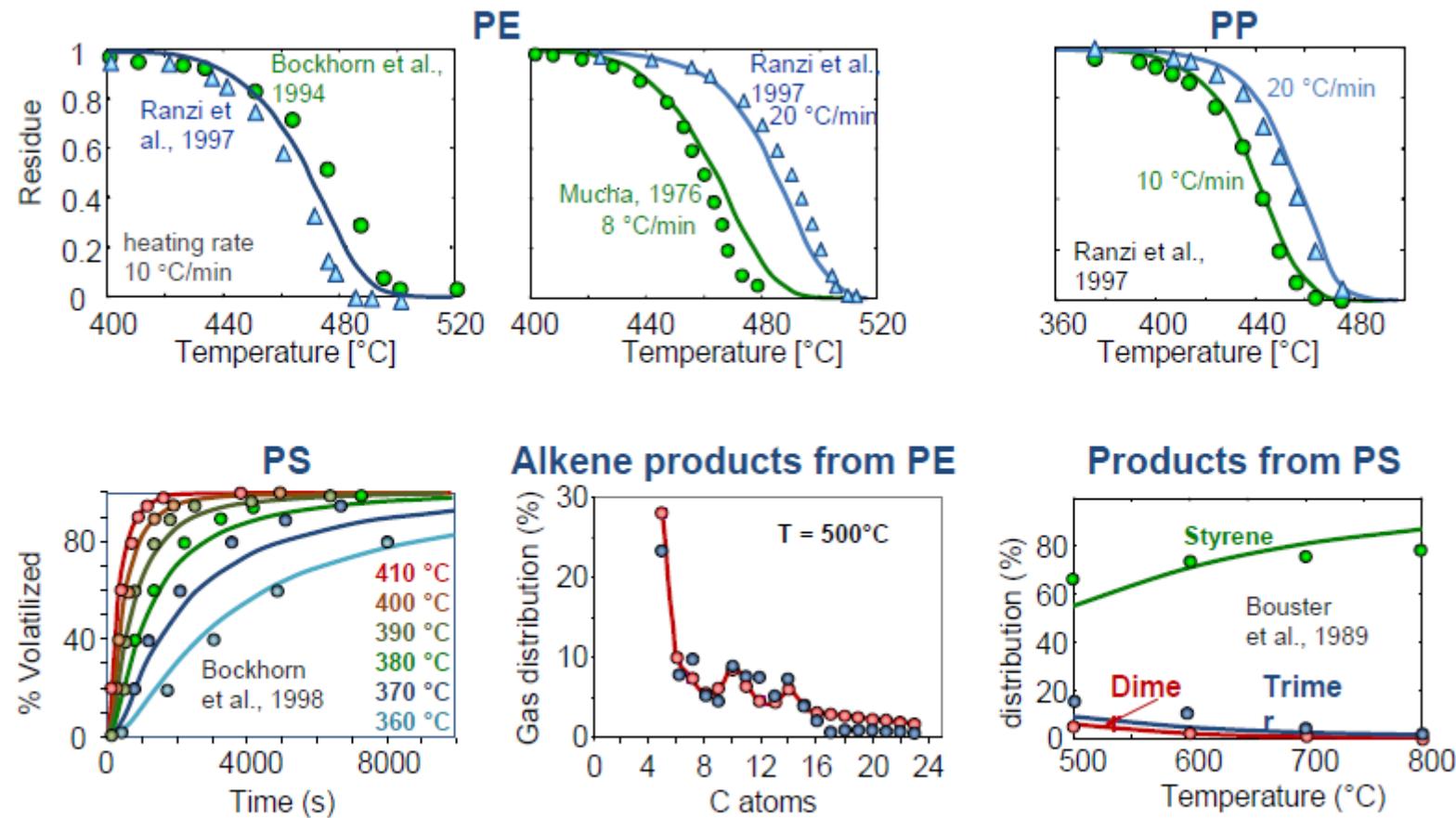
- Chain modification (unsaturations)
 - Chain scission
 - Cross linking
 - Cyclization
- Volatile products
- Char residue

2.2.1.2 Wastes : plastic structure - depolymerization

Side group mechanism



2.2.1.2 Wastes : plastic structure – depolymerization model



Faravelli et al., J.A.A.P., 52 (1999) 87–103

Faravelli et al., J.A.A.P., 60 (2001) 103–121

State of Art in PNU and KIER

▪ 총 사업기간 : 2010.06.01~2012.11.30 (30개월)

▪ 최종 및 단계별 사업목표

가연성 폐기물 종별 연소 동특성 분석 및 연소 모델링 개발

1차년도

- 가연성 폐기물 연료의 종별 연소 정/동특성 해석
- TGA/DSC와 FTIR을 이용한 종별 물리 화학적 기초 특성 해석
- 연소 정/동특성 기초 DB를 통한 연소최적화 시뮬레이터 기초 입력자료 생성
- 신속 고열 동력보일러 연소실 3D 모델링

2차년도

- 개발
- 가연성 폐기물 연소거동특성 분석 및 시뮬레이터를 통한 최적운전기술개발
 - TGA-DSC 를 적용한 연소실 내에서의 연소거동 및 배출가스 특성 해석
 - 연료별 연소 동특성(kinetics)과 연소거동특성해석을 통한 동력보일러 연소 시뮬레이터
(상용코드 기반)
 - Utility 동력보일러에 대한 시뮬레이터 정확성 검증
 - 연소 시뮬레이터를 통한 바이오매스 연소실에서의 고성능, 최적화 운전조건 도출

State of Art in PNU and KIER

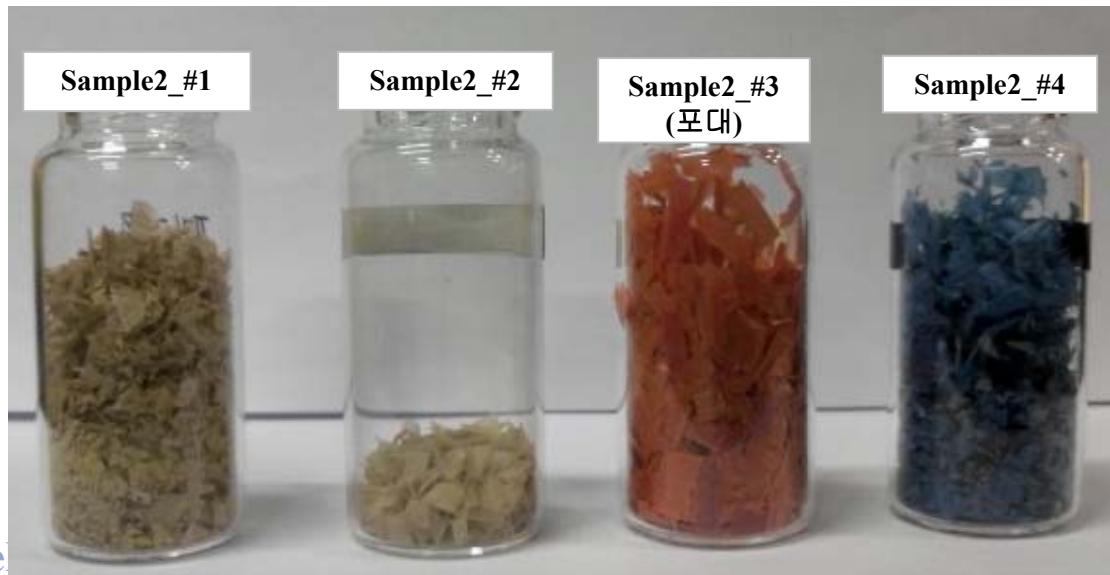
- 가연성 폐기물 연소거동특성 분석 및 시뮬레이터를 통한 최적운전기술개발
 - 샘플종류 : RDF, RPF, 정방샘플(Sample #1, Sample #2-1~4)



Sample #1

RDF

RPF

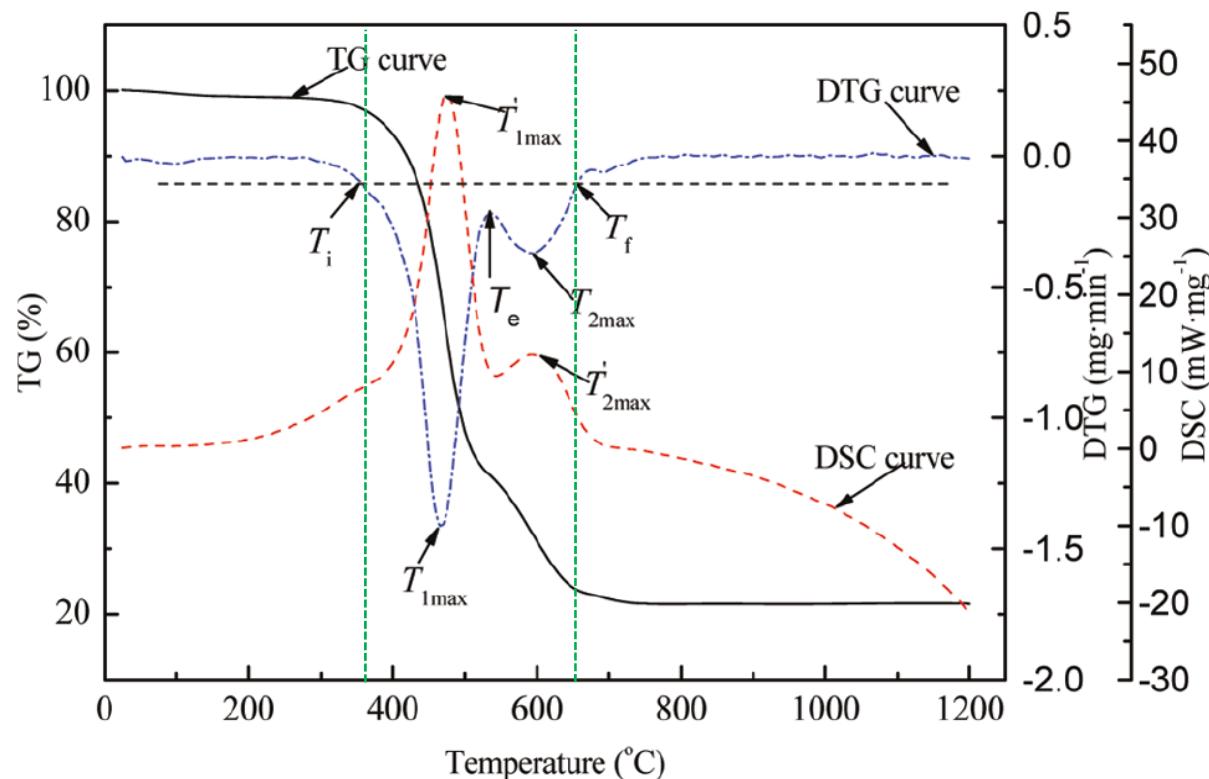


Ch. 2 Solid Fuel

n. from Solid Fuel

State of Art in PNU and KIER

- Ignition & burnout temperature : The temperature of 0.1mg/min(DTG)
- T_{50} temperature : The temperature at the minimum DTG value =Maximum temperature
- Reaction rate : Slope between T_i and T_f as a function of temperature



State of Art in PNU and KIER

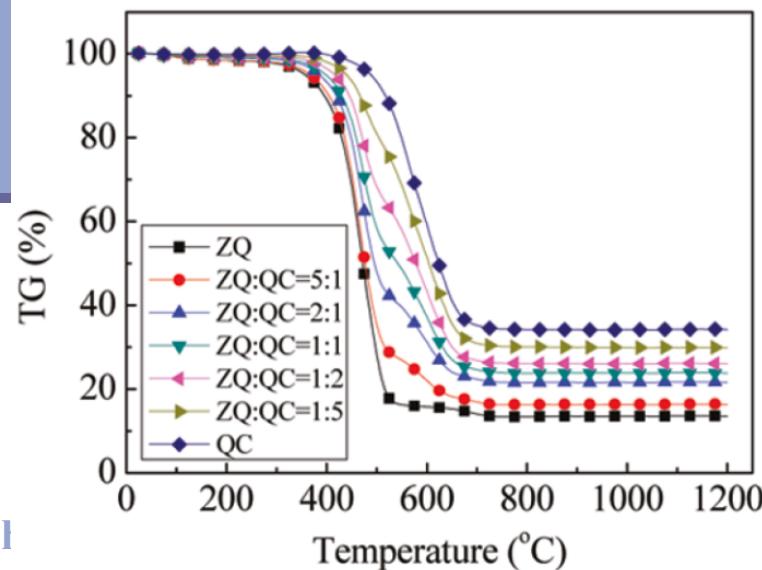
- Reaction rate and kinetics

$$\dot{r}_c = \frac{m}{\Delta t} = k(\rho \frac{3}{4} \pi r_s^3) P_{O_2,\infty} \quad \text{where} \quad k = A \exp\left(-\frac{E}{RT}\right) \Rightarrow \ln k = \frac{-E}{RT} + \ln A$$

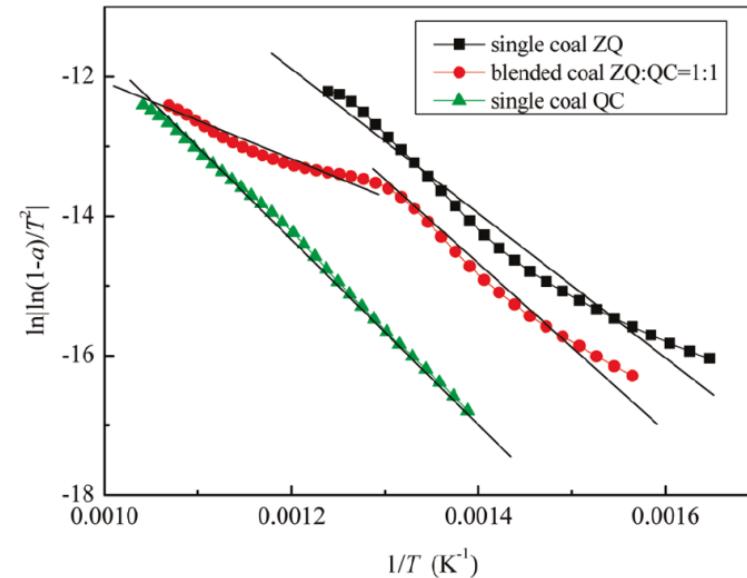
A : pre-exponential factor [1/S],
E : Activation energy [kJ/kg]

Coats-Redfern method (CR)

$$\text{if } n \neq 1, \quad \ln \left| \frac{1 - (1 - a)^{(1 - n)}}{T^2(1 - n)} \right| = \ln \left[\frac{AR}{\beta E} \left(1 - \frac{2RT}{E} \right) \right] - \frac{E}{RT}$$



Cl

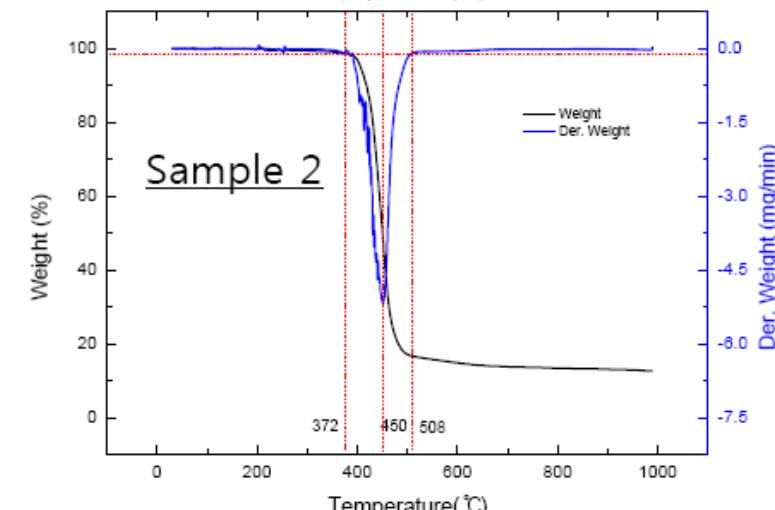
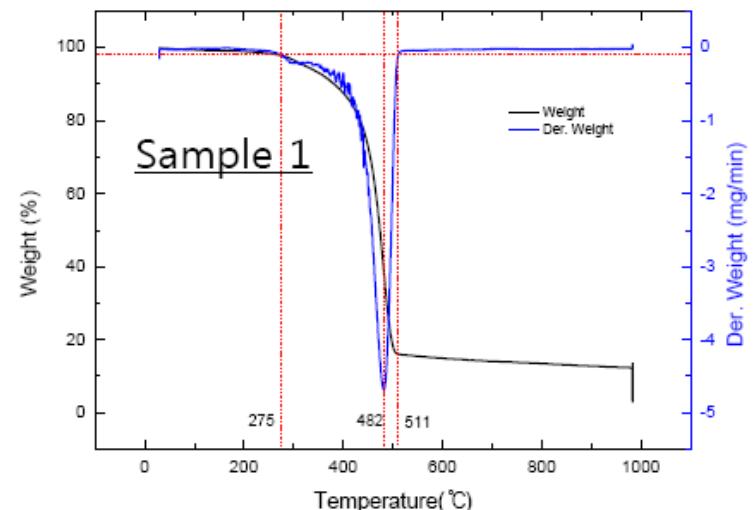
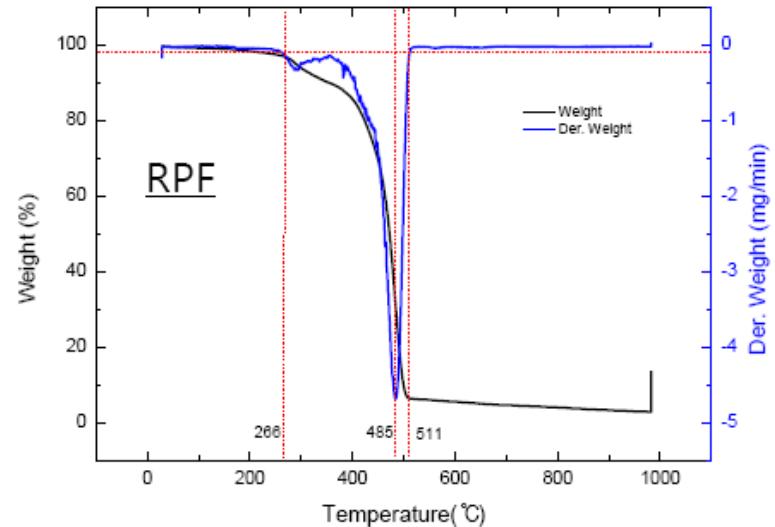
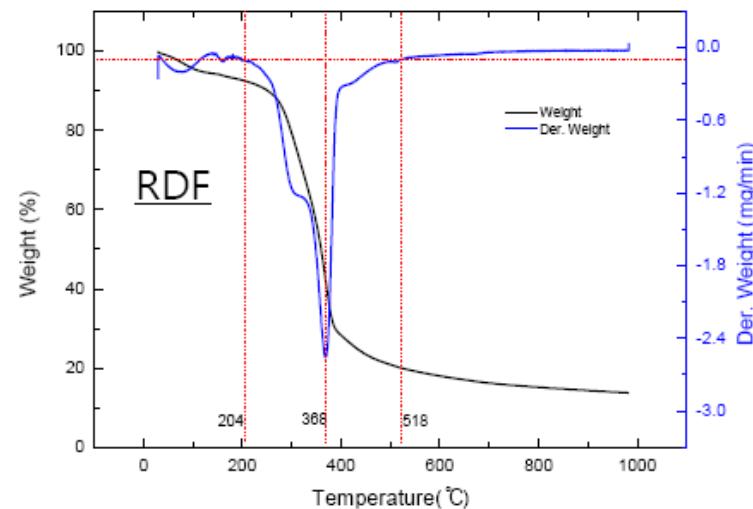


Fuel

State of Art in PNU and KIER

- TGA-DSC를 이용한 폐기물 연료의 열분해 및 연소 정특성 연구

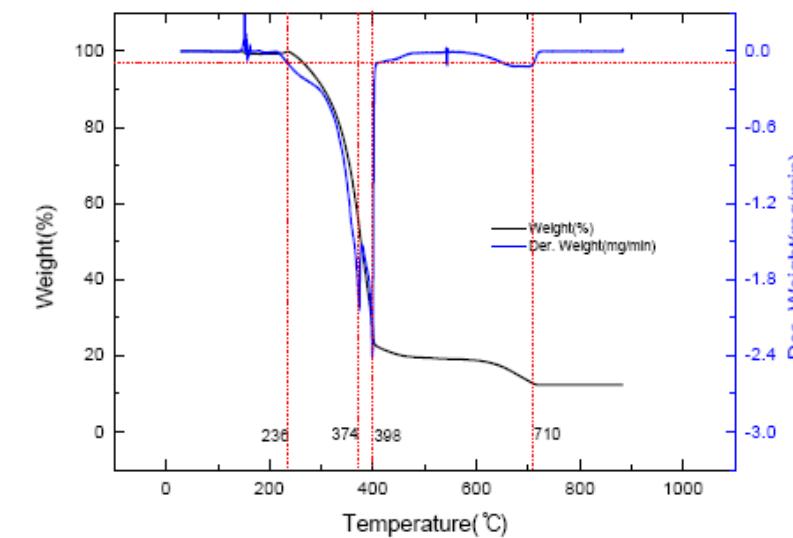
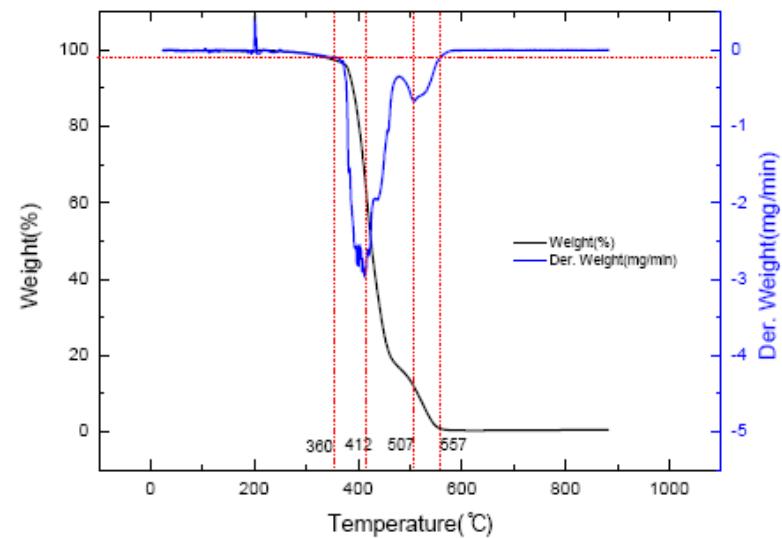
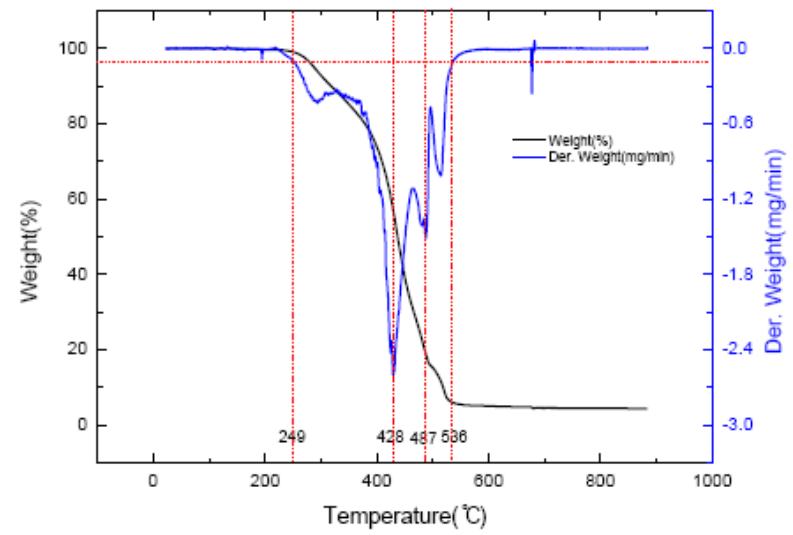
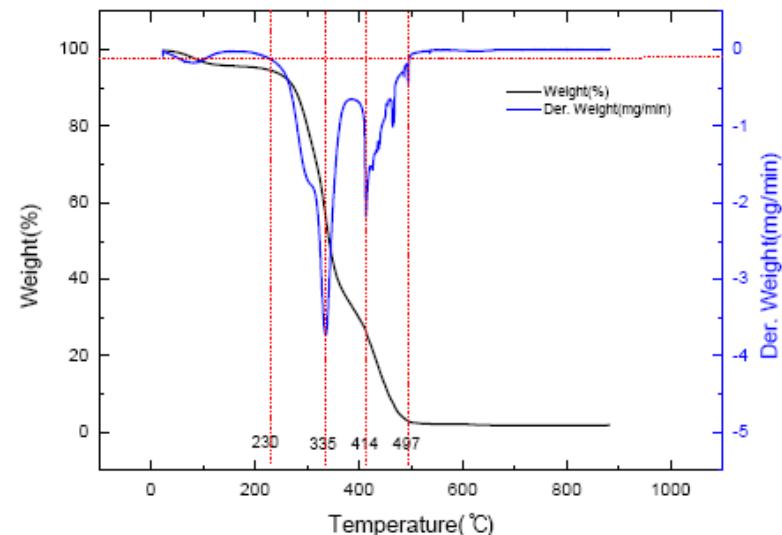
- Pyrolysis process : N₂ condition, up to 1000 °C @ 20 °C/min



State of Art in PNU and KIER

- TGA-DSC를 이용한 폐기물 연료의 열분해 및 연소 정특성 연구

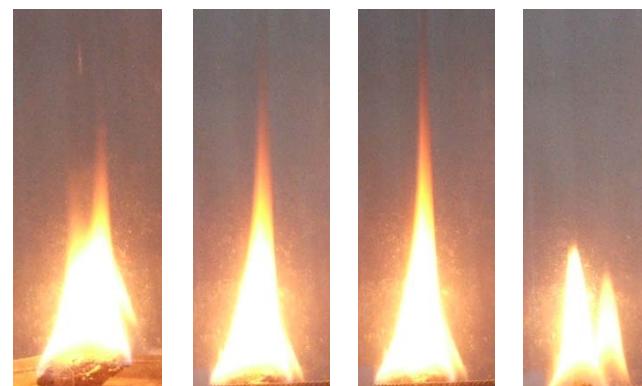
- Oxidation process : Air condition, up to 1000 °C @ 20 °C/min



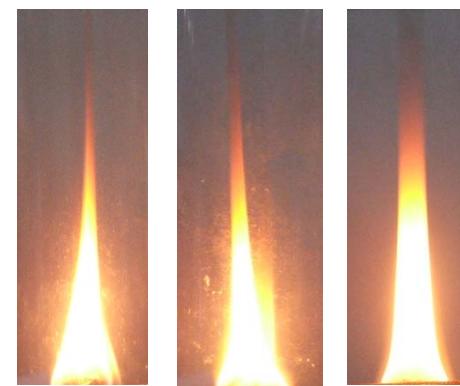
State of Art in PNU and KIER

슬릿버너를 이용한 기초연소특성 해석

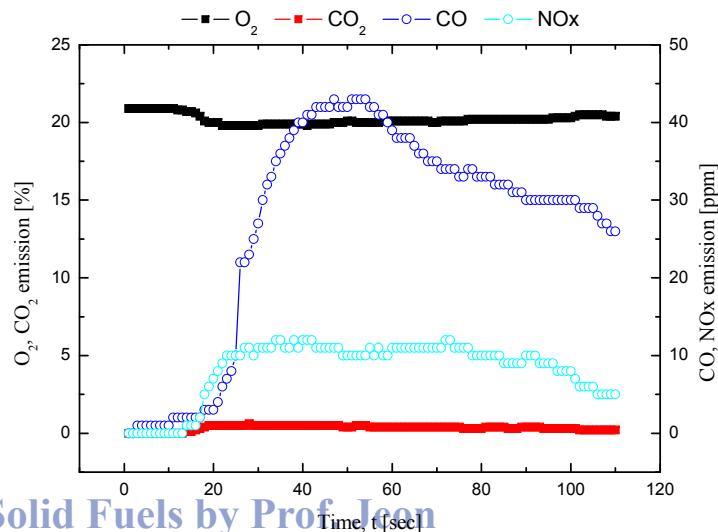
- 가연성 폐기물의 버너 연소를 통한 화염의 성장, 소멸과정 및 구조특성분석 및 배출가스 특성 분석
- 폐기물 버너 연소시 배출가스(NOx , CO , CO_2 , O_2) 특성분석



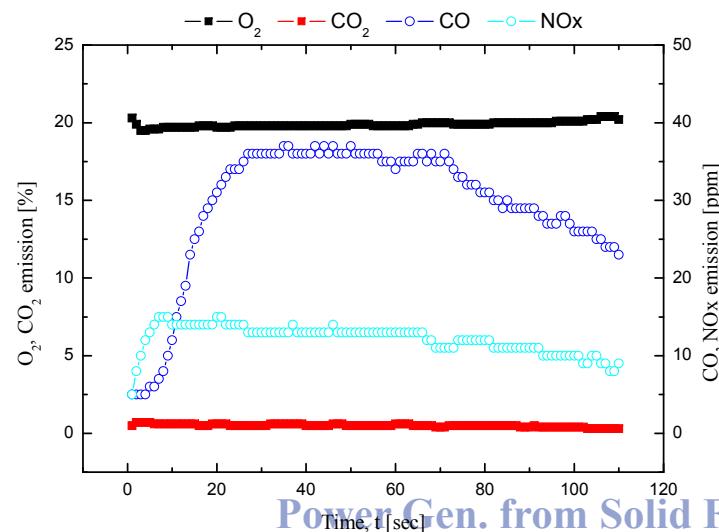
(a) Burning process



(b) Flame shapes of samples



Ch. 2 Solid Fuels by Prof. Jeon



Power Gen. from Solid Fuel

Table 2.8 Amount of wastes in Germany (Becker et al. 2007)

	2002	2003	2004	2005
Waste volume	1,000 t			
Total	381,262	366,412	339,368	331,876
Building rubble and demolition waste (incl. roadway rubble)	240,812	223,389	187,478	184,919
Mining spoil (non-hazardous waste)	45,461	46,689	50,452	52,308
Wastes from production processes and industry	42,218	46,712	53,005	48,094
Municipal wastes	52,772	49,622	48,434	46,555

All values in thousands of tonnes

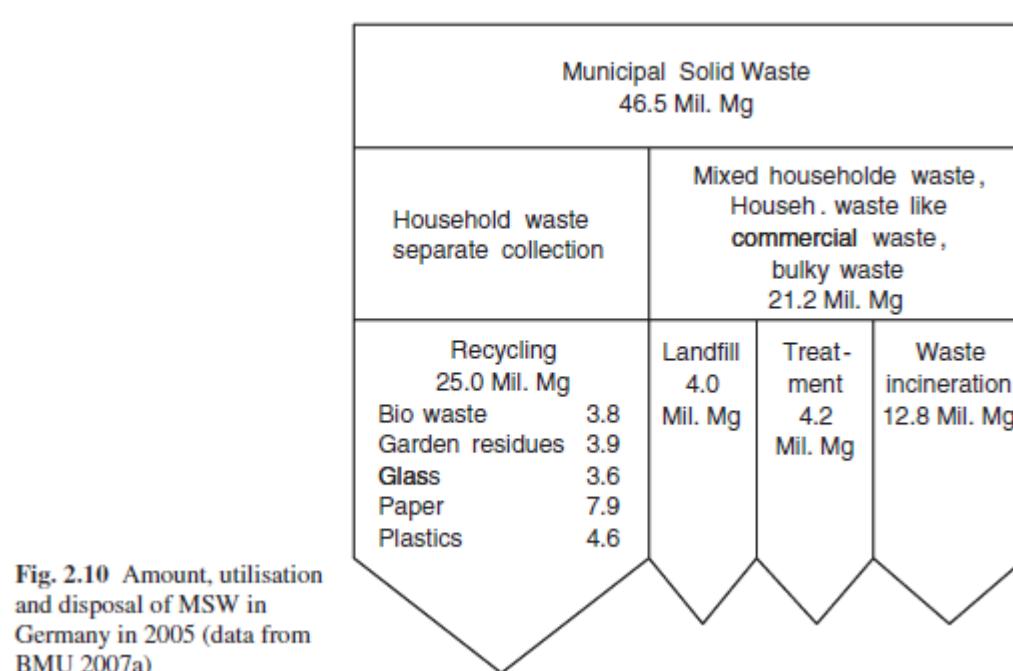


Fig. 2.10 Amount, utilisation and disposal of MSW in Germany in 2005 (data from BMU 2007a)

2.2.1.4 Sewage Sludge

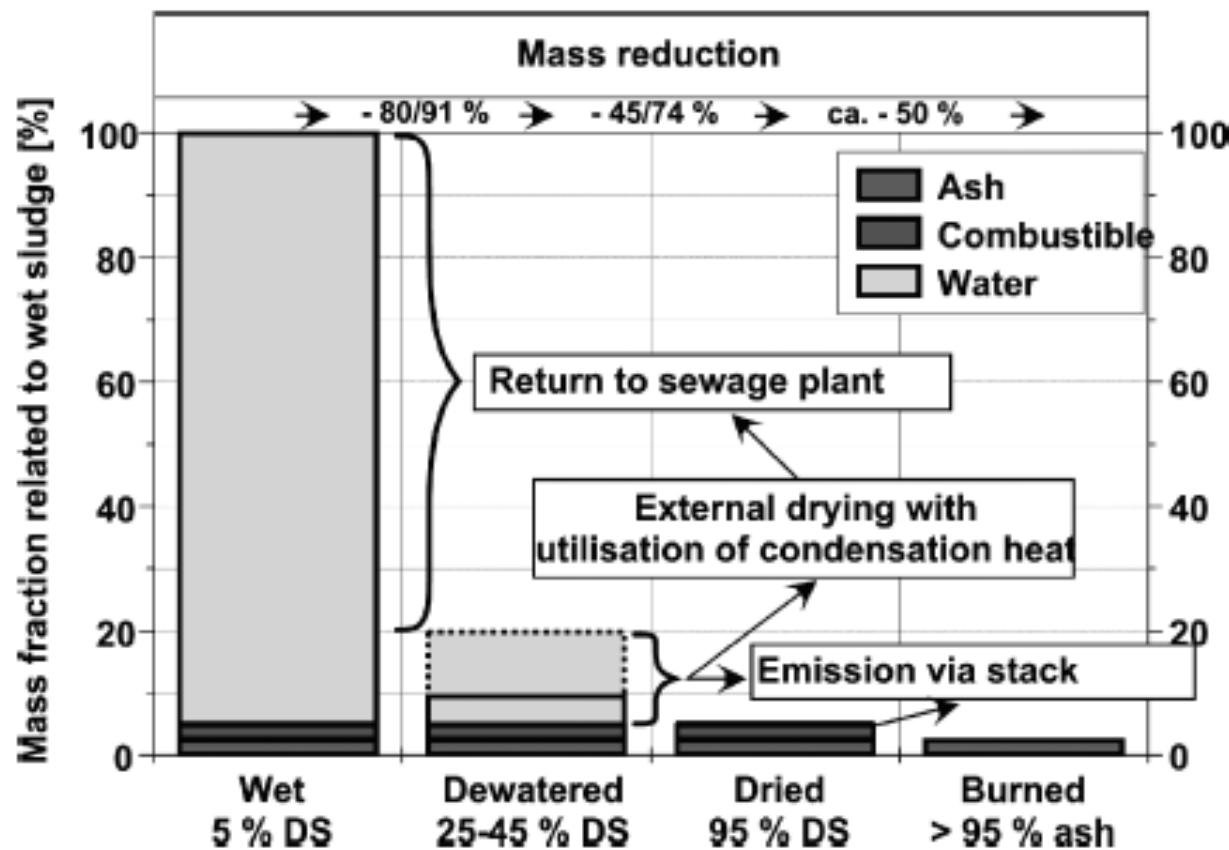


Fig. 2.11 Effect of treatment on the volume reduction of sewage sludge (Gerhardt et al. 1996)

2.2.2 Considerations of the CO₂ Neutrality of Regenerative Fuels

Fig. 2.12 Breakdown of the CO₂ emissions in *Miscanthus* processing (Kicherer 1996)

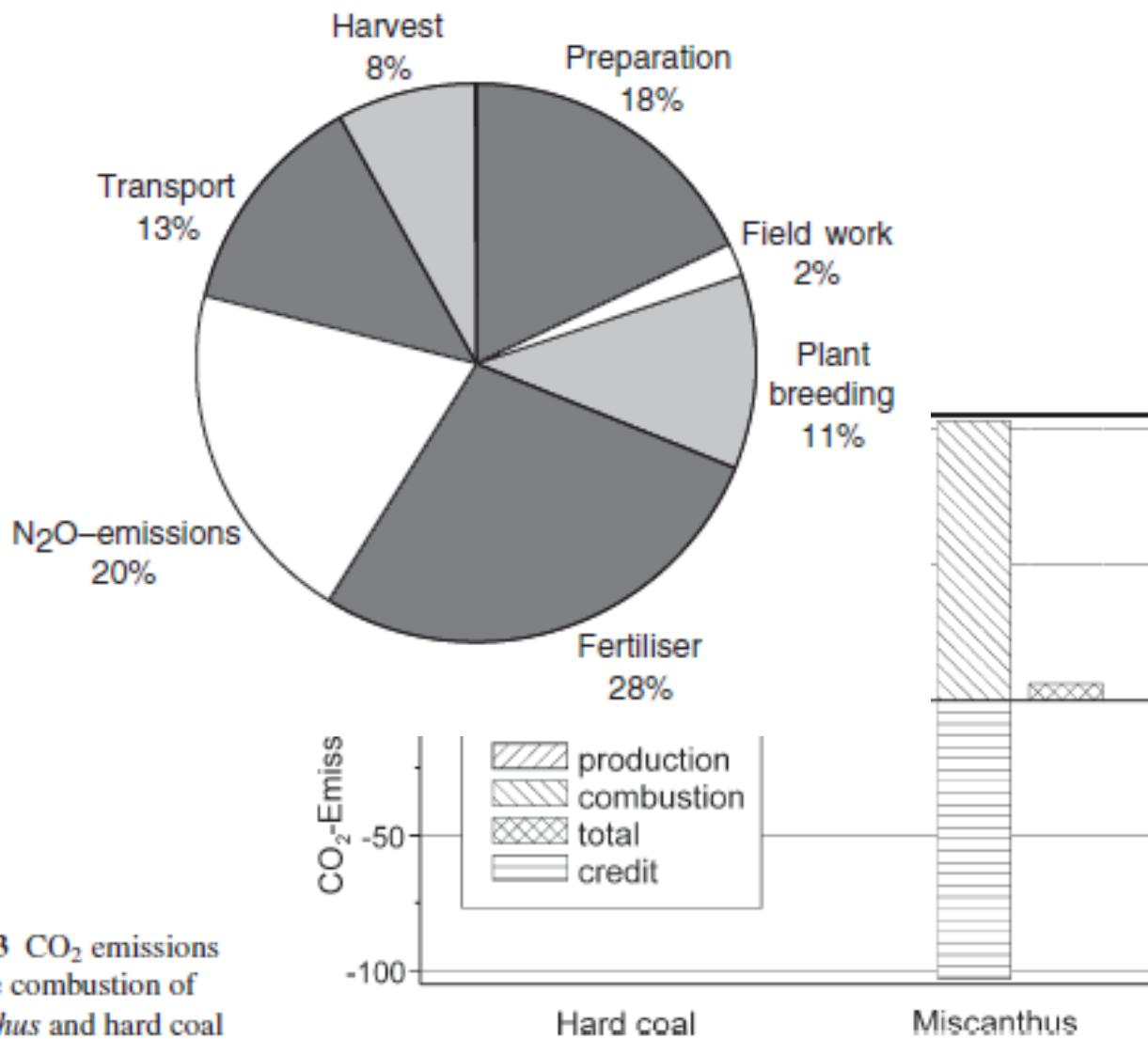


Fig. 2.13 CO₂ emissions from the combustion of *Miscanthus* and hard coal

2.2.2.2 Harvest Ratios

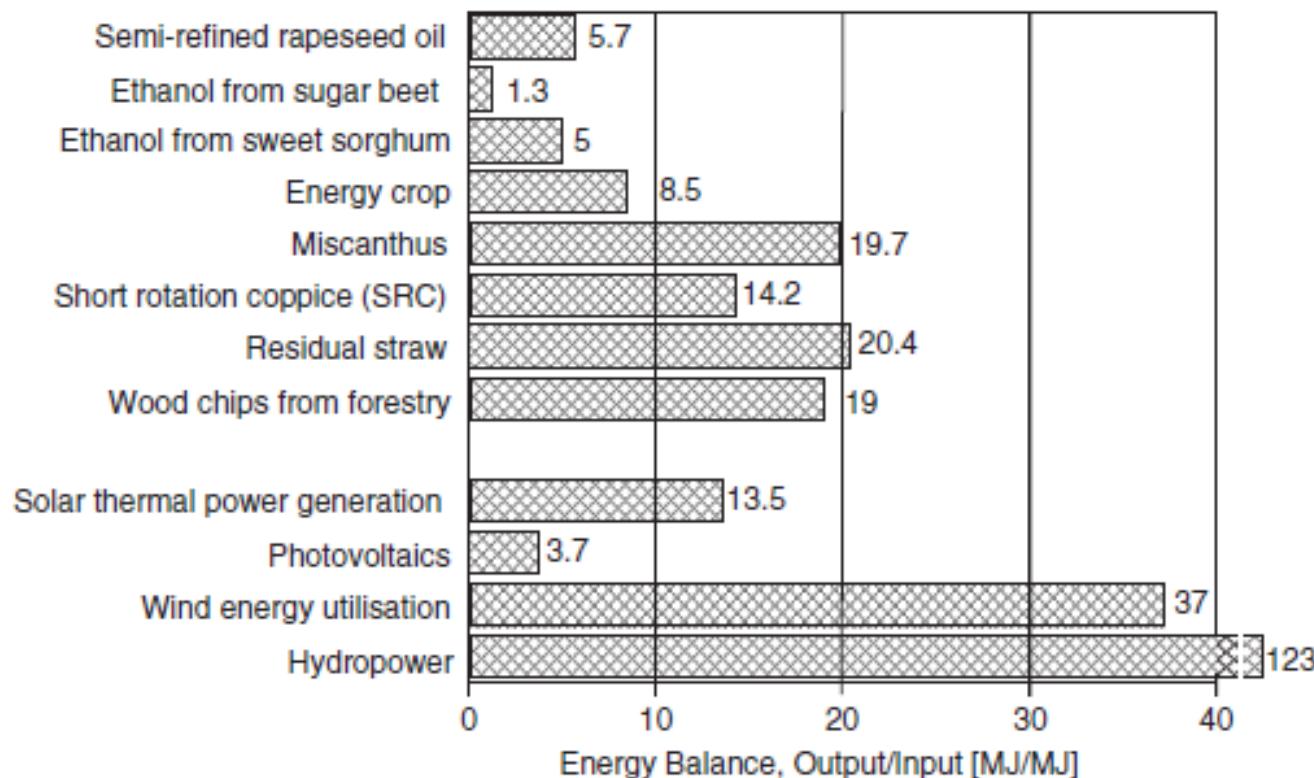


Fig. 2.14 Harvest ratios of various biomass types (Hartmann and Strehler 1995)

2.2.3 Fuel Characteristics of Biomass

2.2.3.1 Biomass from Farming and Forestry

Table 2.9 Components of biomass (% by wt) (Kicherer 1996)

	Lignin	Cellulose	Hemicellulose	Ash	Other
Hardwood	26–31	40–48	19–25	1	3
Softwood (coniferous wood)	22–25	35–43	21–30	1	3
Wheat straw	18	32	37	8	5
<i>Miscanthus</i>	18	40	34	3	7

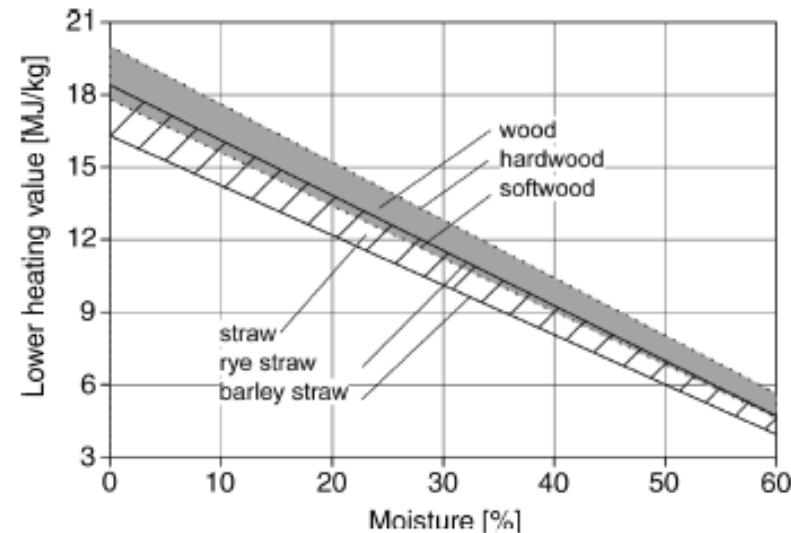


Fig. 2.15 Calorific value as a function of the moisture content

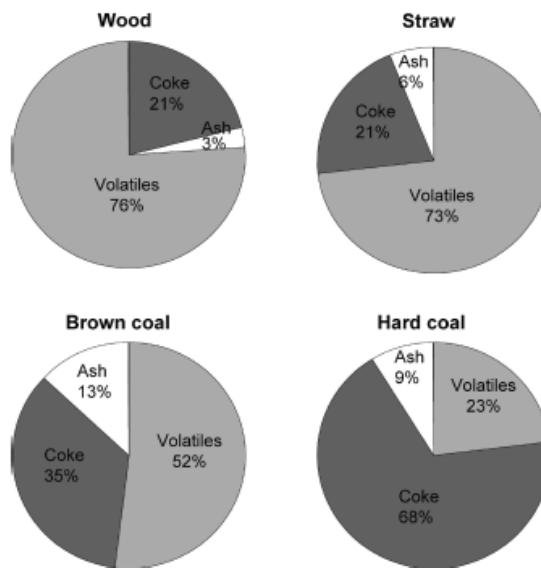


Fig. 2.16 Volatile matter, residual char and ash contents of various biomasses and coals

Table 2.10 Fuel composition of biomass types (Kalschmitt 2001; Lewandowski 1996; Hartmann and Strehler 1995; Clausen and Schmidt 1996; Obernberger 1997; Spliethoff et al. 1996)

	Straw		Wood		<i>Miscanthus</i>		Whole cereal plants		Hard coal (comparison)	Brown coal (comparison)
	Typical value	Range	Typical value	Range	Typical value	Range	Typical value	Range	Göttelbom	Fortuna
Moisture content [%]	15	10–20	45	20–60	20	10–30	15	10–20	7	55
LHV, raw [MJ/kg]	14.8	12.5–16.4	9.6	5.7–15.5	14.0	11.2–16.6	14.9	12.5–16.6	27.9	8.7
LHV, dry ash-free [MJ/kg]	18.7	17.5–19.0	19.5	18.5–20.0	18.5	18–19	18.7	17.5–19	30.2	22.2
Ash % dry	4.5	3–7	0.5	0.3–4	2.5	1.5–5.0	4.0	3–7	8	9
Volatile matter % dry	78	75–81	80	70–85	80	78–84	78.0	75–81	35.1	53
C	47.0	46–48	50	49–52	48	47–50	47.0	46–48	74.3	62.8
H	6.0	5.4–6.4	5.8	5.2–6.1	6.0	5.2–6.5	6.0	5.3–6.8	5	4
N	0.5	0.3–1.5	0.2	0.1–0.7	0.3	0.1–0.4	1.4	0.4–1.7	1.5	0.5
S	0.15	0.10–0.2	0.05	< 0.1	0.1	0.02–0.13	0.1	0.07–0.11	1	0.5
Cl	0.4	0.1–1.1	0.02	< 0.1	0.3	0.1–0.4	0.3	0.25–0.5	0.2	
O (difference)	41.5		43.4		42.8		41.2		9.5	23.2

Fig. 2.17 Ranges of nitrogen, sulphur and chlorine contents in biomass compared to hard coal

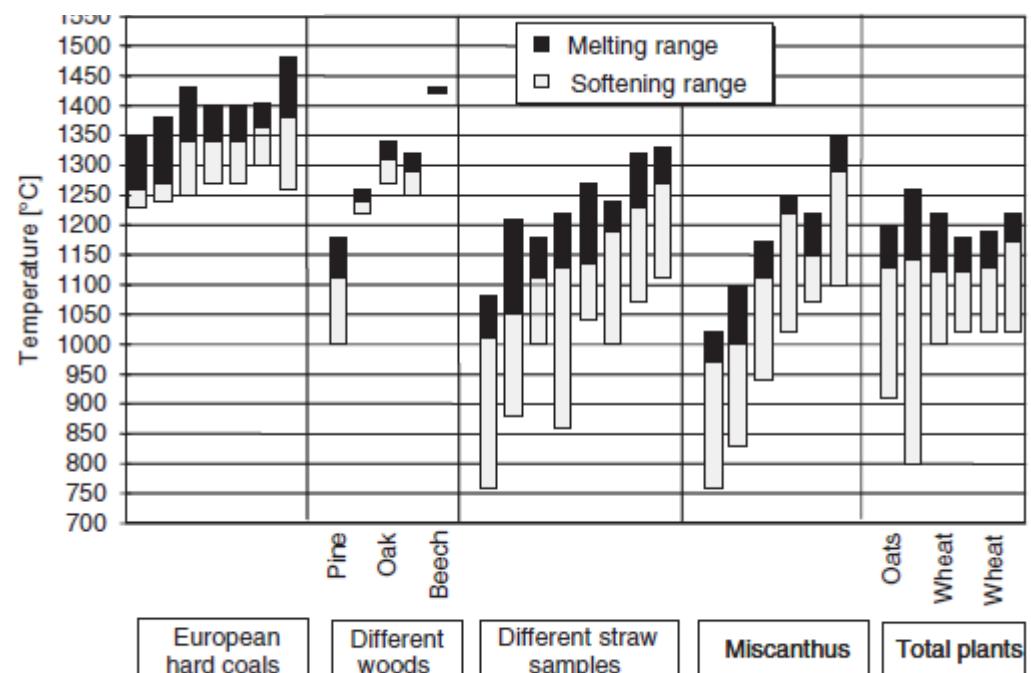
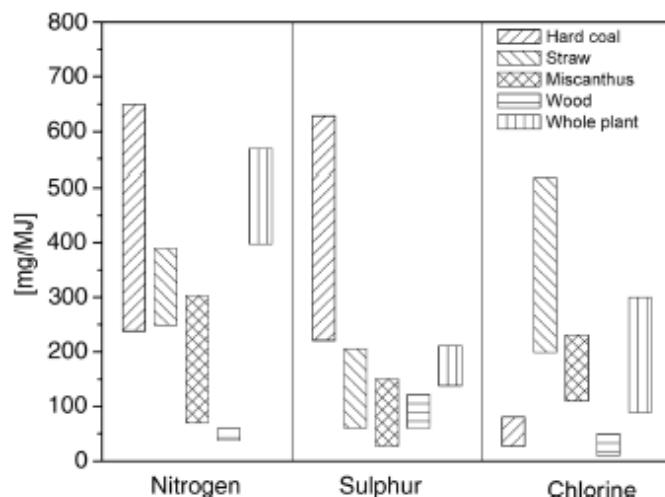


Table 2.11 Ash composition (%) of a woody brown coal type

	Straw	Sp
SiO ₂	65.43	29
Al ₂ O ₃	0.59	2
Fe ₂ O ₃	1.17	6
CaO	9.47	37
MgO	1.76	5
K ₂ O	18.07	9
Na ₂ O	0.20	1
SO ₃	0.98	3
TiO ₂	0.10	0
ZnO	0.00	0
P ₂ O ₅	2.25	3

Table 2.13 Energy densities of various biomasses

Fuel	Density ρ [kg/m ³]	Lower heating value (LHV) [MJ/kg]	Energy density [GJ/m ³]
Straw, large-size cubic bales	150	14.4	2.2
Straw, chaff	70	14.4	1.0
Straw, pellets	520	14.4	7.5
Whole plant, large-size cubic bales	220	14.4	3.2
<i>Miscanthus</i> , large-size cubic bales	130	14.4	1.9
Wood chips	250	15.3	3.8
Hard coal	870	28	24.4
Brown coal	740	10	7.4

Table 2.12 Densities (at a moisture content of 15%) of various biomasses (kg/m³) (Kicherer 1996; Hartmann and Strehler 1995)

Biomass	Density		Bulk density	
Herbaceous biomass:		Large-size cubic bales	Round bales	Chaff
Straw	150		120	70
<i>Miscanthus</i>	130			120
Whole cereal plants	220		190	130
Grain				560
Wood	Cordwood 300–500		Chips 200–300	Pellets 650

2.2.3.2 Wastes

Table 2.14 Composition of residual MSW (example) (Hoffmann 2008)

Fraction	Fraction of waste [wt%]	Moisture [wt%]	LHV [kJ/kg]
Organics	35.0	65.0	7,000
Paper, cardboard	8.0	25.0	11,000
Wood	3.0	31.0	15,000
Fine fraction (< 10 mm)	19.0	23.0	3,500
Combined materials	6.0	12.0	12,000
Other	5.0	5.0	6,000
Textiles	4.0	28.0	14,000
Plastics	10.5	6.0	22,500
Fe metal	2.0	0	0
NF metal	0.5	0	0
Glass	3.0	0	0
Minerals	3.0	0	0
Pollutants	1.0	0	5,000
Average		33.0	8,438

H = 4–5 S = 0.2–0.7 O = 17–30 N = 0.3–0.45 Cl = 0.5–1.5	water free	Deformation temp. 1,100	Pb = 0.6–2
Ash ≈ 25 Moisture ≈ 30 Combustable = 45		Fluid temp. 1,260	Cu = 0.12–0.78 Fe = 10–100 Zn = 0.44–2.3 Sn = 0.05–0.32 Cr = 0.02–0.88
		Bulk density in kg/m ³	Cd = 0.003–0.012 Ba = 0.084–1.225
		Bulk 90–120	
		Collection vehicle 350–550	
		Receiving bunker 200–300	

2.2.3.3 Refuse-Derived Fuel (RDF)

Fig. 2.19 Lower heating value of waste in different countries (Source: Martin)

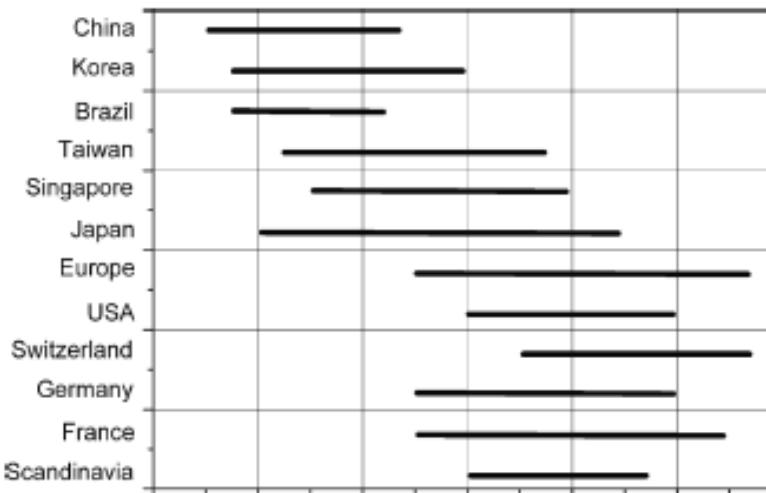


Table 2.16 Composition of various RDFs, showing the influence of the input material (Fehrenbach et al. 2006)

Input material	Input	Municipal solid waste			Household-like commercial waste				
		hcf MBT	DS MBS	DS MPT	Rich in paper and cardboard	Input	RDF	Rich in plastics	Input
									RDF
Moisture	[%]	33.8	10.7	14.8	14.7	21.1	7.8	20.2	7.4
Carbon, fossil	[%]	10.1	27.6	17.1	16.9	11.2	23.9	15.1	31.4
Carbon, organic	[%]	12.8	19.4	21.5	21.7	14.9	23.3	12.9	19.3
Chlorine	[%]	0.48	0.62	0.78	0.77	0.85	0.99	1.43	1.6
Sulphur	[%]	0.2	0.17	0.25	0.25	0.27	0.15	0.27	0.15
Cadmium	[mg/kg]	6.7	7.03	6.7	6.6	11.6	9.8	19.4	18.8
Mercury	[mg/kg]	0.24	0.24	0.27	0.26	0.27	0.27	0.5	0.51
Antimony	[mg/kg]	11.7	12.6	8.25	8.2	11.9	12.9	15.1	18.1
Arsenic	[mg/kg]	3.2	2.1	2.24	2.2	2.8	1.7	2.9	1.65
Lead	[mg/kg]	204	168	228	127	356	189	436	284
Chromium	[mg/kg]	256	290	332	329	267	342	274	344
Fe metal	[%]	3.41	0.01	0.01	0.01	2.7	0.008	2.7	0.001
Non Fe metal	[%]	0.39	0.02	0.001	0.002	0.4	0.0012	0.4	0.001
LHV	[MJ/kg]	9.6	21.6	17.4	17.4	11.2	21.2	11.8	23.3

2.2.3.4 Sewage Sludge

Fig. 2.20 Calorific values of municipal sewage sludge (Gerhardt 1998)

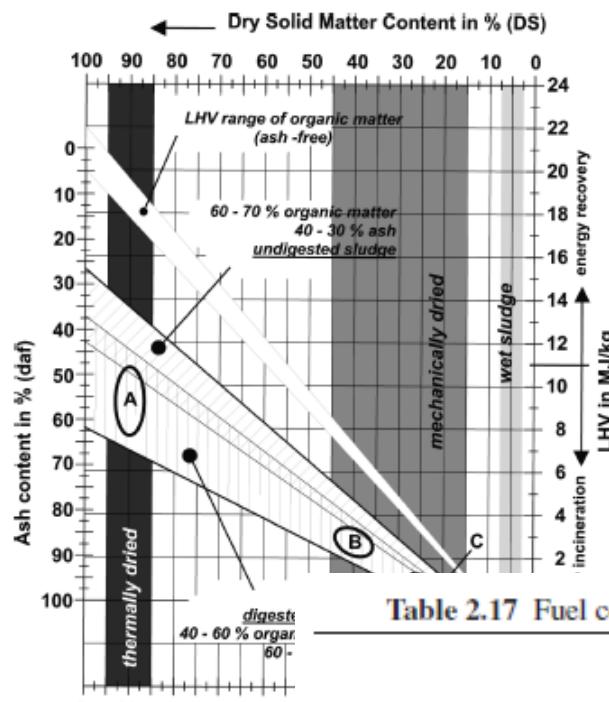


Table 2.17 Fuel composition of sewage sludge (Gerhardt et al. 1997; Gerhardt 1998)

	Dewatered sewage sludge			
	Typical value	Range	Hard coal	Brown coal
Water	Moisture content [%]	55 (dewatered) 5 (thermally dried)	7	55
	Lower heating value (LHV) raw [MJ/kg]	3.6 (dewatered) 10.2 (thermally dried)	27.9	8.7
	Lower heating value (LHV) dry [MJ/kg]	10.9	8.8–14.4	30.2
	Ash % dry	46.9	39–53	8.3
	Volatile matter % dry	51	28–55	34.7
	Fixed C dry	2.5	1–24	57
	C	25.5	20–40	72.5
	H	5	2–5	5
	N	3.3	2–5	1.3
	S	1.1	0.6–7	0.9
	Cl	0.1	0.02–0.6	0.1