Pressurized Coal Pyrolysis and Gasification at High Initial Heating Rates

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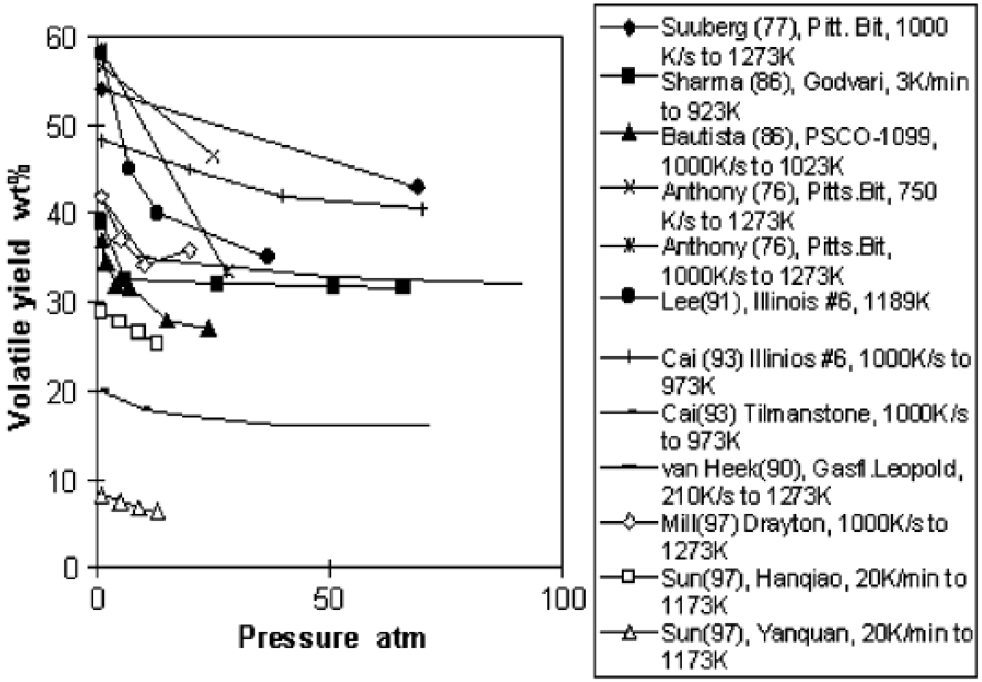
Outline

- Review of the influence of pressure and heating rate on coal devolatilization
- Description of facilities
- Description of experimental findings
- Conclusions

Literature Review: Mass Release

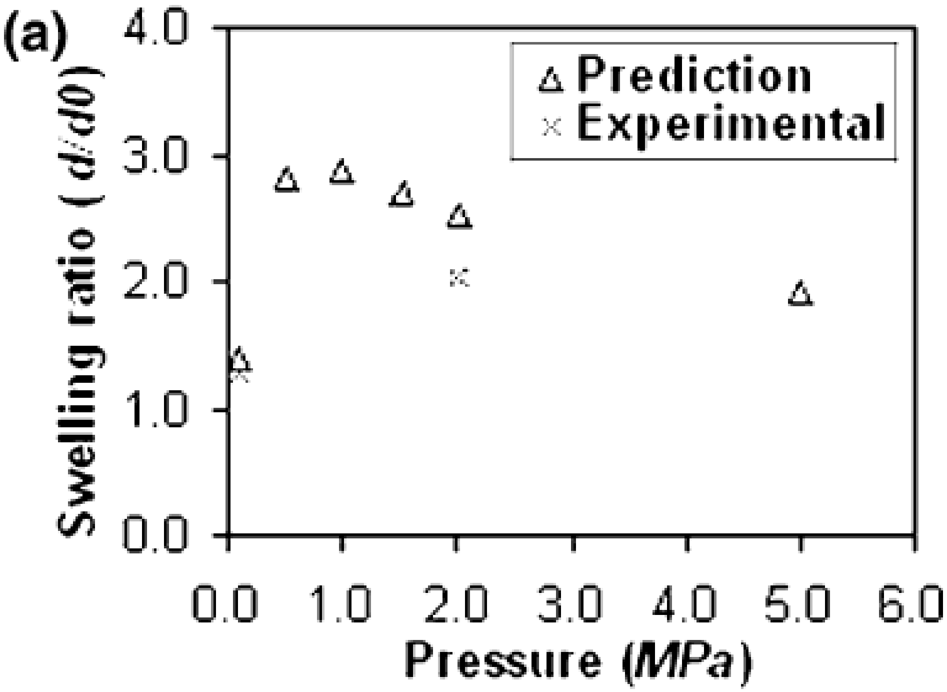
- Effect of increasing pressure
  - Inhibits release of tar
  - More light gases produced by cross-linking reactions
  - Net decrease in volatiles
- Effect of increasing heating rate
  - Causes devolatilization to occur at higher temperatures
  - Higher rate of devolatilization
  - Higher yield of volatiles, especially tar
- CPD model predicts experimental trends

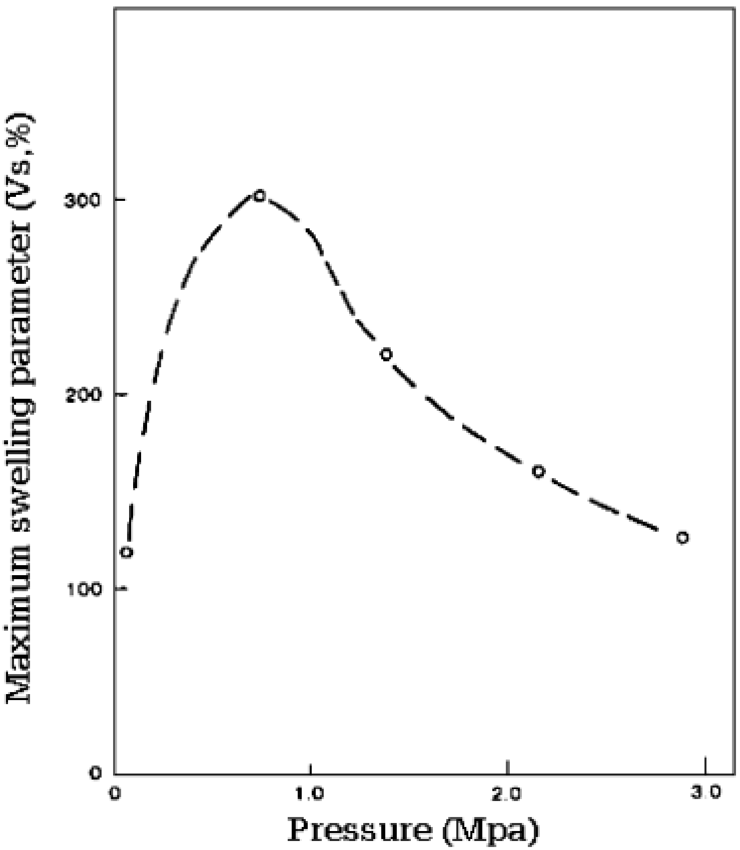


Shan G. PhD thesis, Department of Chemical Engineering, University of Newcastle (NSW), Australia, 2000.

Yu, J., J. A. Lucas and T. F. Wall, Progress in Energy and Combustion Science, 33(2), 135-170 (2007).

Literature Review: Swelling





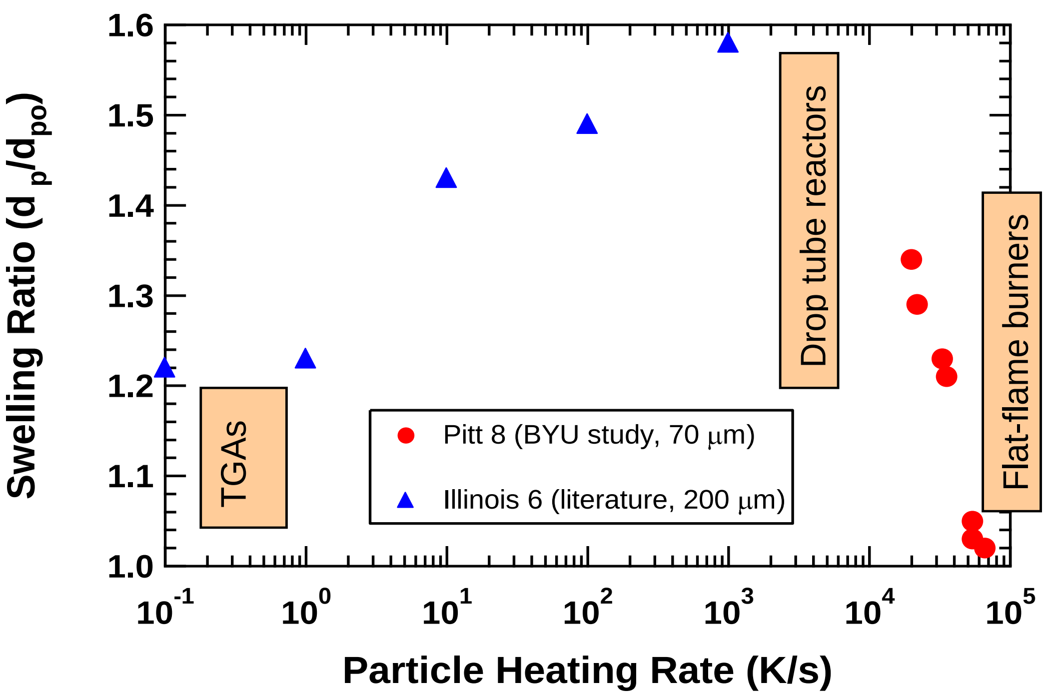
- Effect of pressure on swelling at ~10^4 K/s

Yu, J., D. Harris, J. Lucas, D. Roberts, H. Wu and T. Wall, *Energy & Fuels,* **18**(5), 1346-1353 (2004).

Yu, J., J. A. Lucas and T. F. Wall, Progress in Energy and Combustion Science, 33(2), 135-170 (2007).

Lee, C. W., R. G. Jenkins and H. H. Schobert, Energy & Fuels, 6(1), 40-47 (1992).

Literature Review: Swelling



- Effect of heating rate on swelling
  - Pressure effect mostly investigated at ≤10^4 K/s

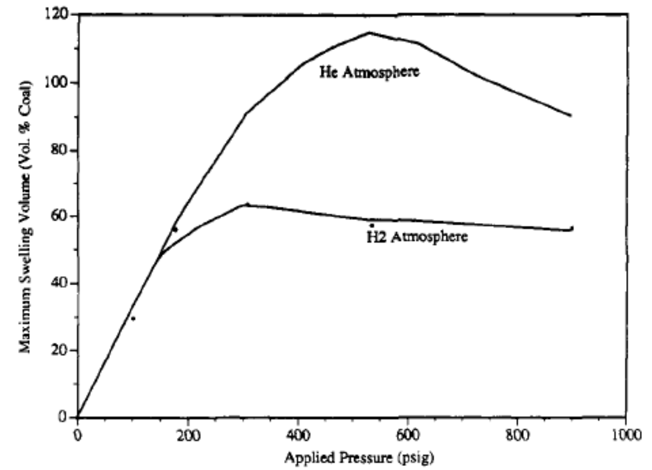


Figure 3. Effect of pressure on maximum swelling volume (V_s) of Illinois No. 6 coal measured at 80 °C/min heating rate, in hydrogen and helium atmospheres.

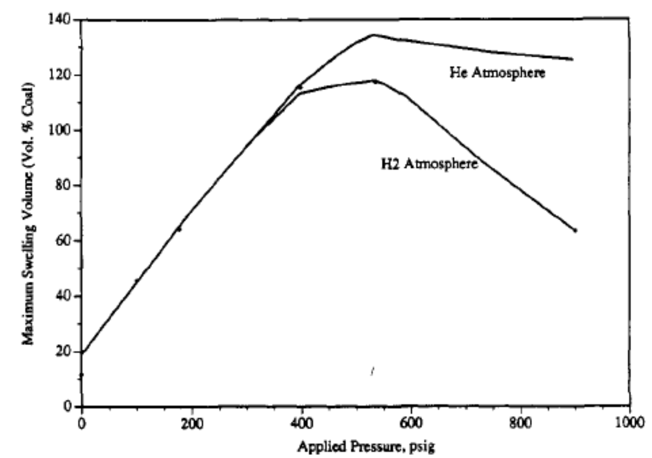


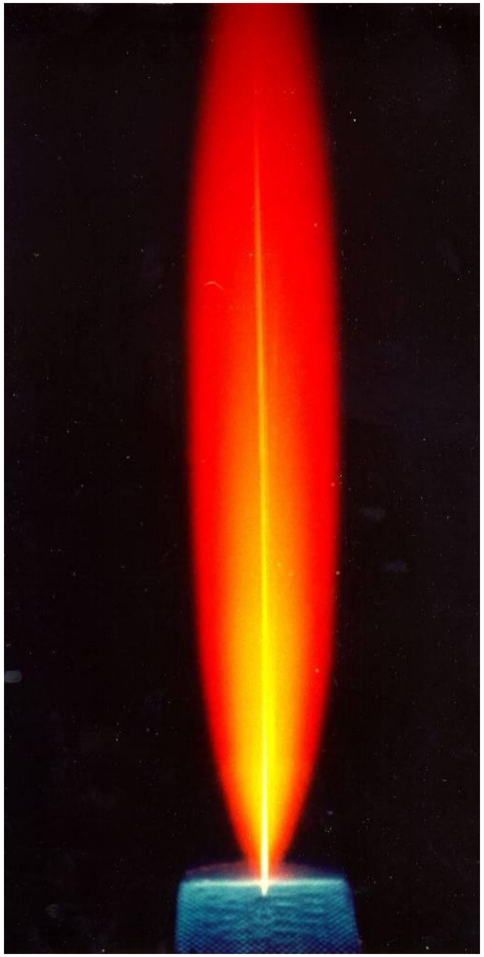
Figure 4. Effect of pressure on maximum swelling volume (V_s) of Illinois No. 6 coal measured at 160 °C/min heating rate, in hydrogen and helium atmospheres.

Gale, T. K., C. H. Bartholomew and T. H. Fletcher, *Combustion and Flame,* **100**(1-2), 94-100 (1995).

Lee, C. W., R. G. Jenkins and H. H. Schobert, *Energy & Fuels,* **6**(1), 40-47 (1992).

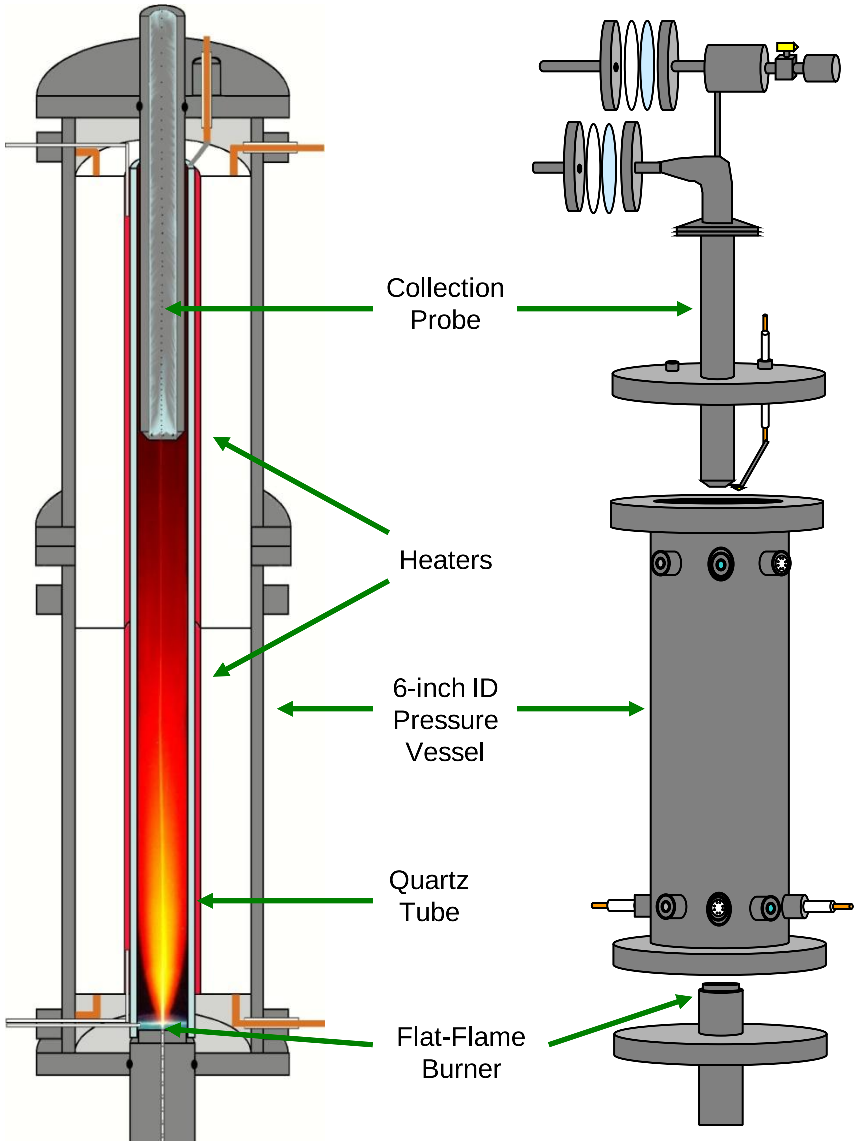
Atmospheric Flat-Flame Burner (FFB)

- Advantages:
  - Char and soot formation at high heating rate (~10^5 K/s)
  - Fueled by CH_4 or CO
    - Allows temperature flexibility (1100 K to 2000 K)
  - Adjust stoichiometry for % O_2 in post-flame zone
  - Very fast heat-up and shut-down times for ease of use
  - Residence time adjusted easily
- Disadvantages:
  - Limited to experiments at ambient pressure



Upgraded HPFFB

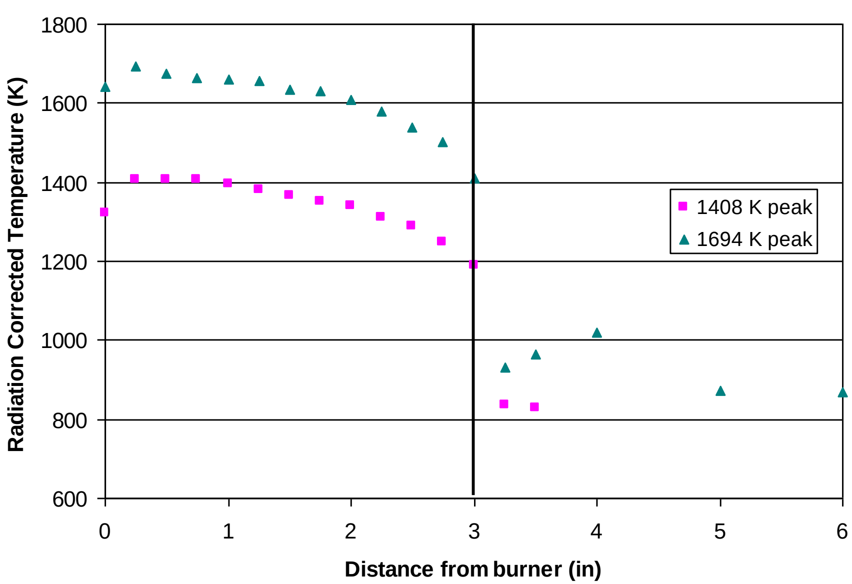
- Changed to up-flow
  - Reduces wear on the burner
- Probe moves to change residence time
  - Up to 800 ms for 1 section
  - Up to 1600 ms for 2 sections
  - Very short residence times available
- Operational pressures of 2.5-15 atm
  - Upgradeable to 30 atm
- Uses either CH_4 or CO with some H_2
  - Greater flexibility in gas composition
  - CO will not form soot
- Optical access available near burner
  - Check particle feeding
  - Limited optical particle velocities
- Faster startup
- Easier to disassemble

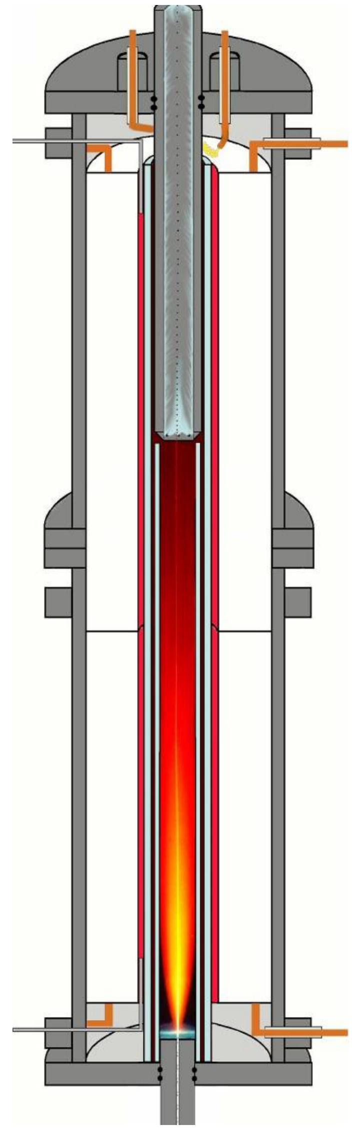


More Recent Upgrades

- Reduced burner diameter from 2” to 1”
  - Easier maintenance
  - Lower fuel costs
  - Closer match to collection probe ID
- New particle feeder
- More effective quench

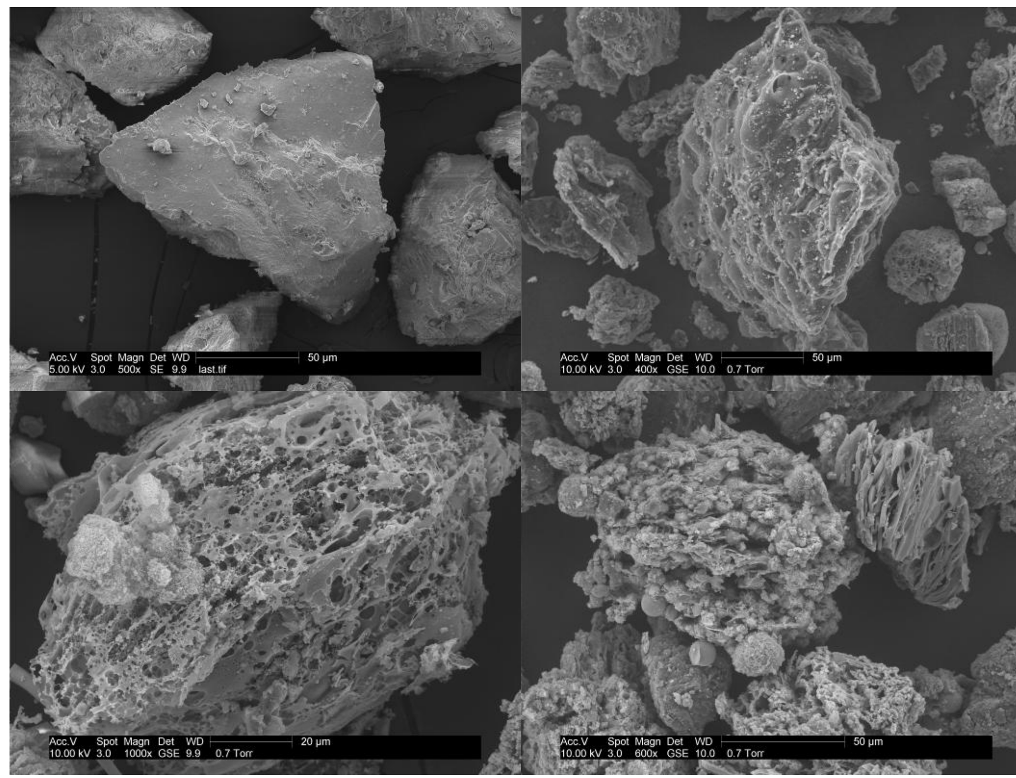
15 atm HPFFB Temperature Profiles, Quench at 3"





Steam Gasification of Wyodak Coal

- Experimental Conditions
  - 2.5 atm
  - 1640 K, Φ=1.07
  - Fuel mixture
    - 84 mol% H_2 with CH_4
  - Gas composition
    - 27.4 mol % H_2O
    - 3.0 mol % CO_2
    - 1.8 mol % H_2
    - 0.06 mol % O_2
  - 77 μm particles



Steam Gasification of Wyodak Coal

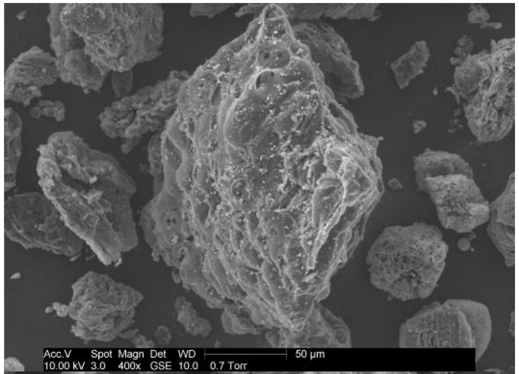
- 90 ms char fully pyrolyzed
  - CPD predicts 62% MR_{daf} in ~30 ms
- Little change from 210-870 ms
  - Linear gas temperature decrease of ~300 K from peak over 14 inches (660 ms)
- Highly porous chars
  - Coal ρ_p = 1.49
  - N_2 surface area of 360 m^2/g at 210 ms
- Zone II behavior near burner
  - d_p and ρ_p changing in first 210 ms
  - Zone III calculations predict 100% conversion ~30 ms after full pyrolysis

90 ms

MR_{daf} = 68.6%

ρ_p=0.76 g/cc

d/d_0=0.85

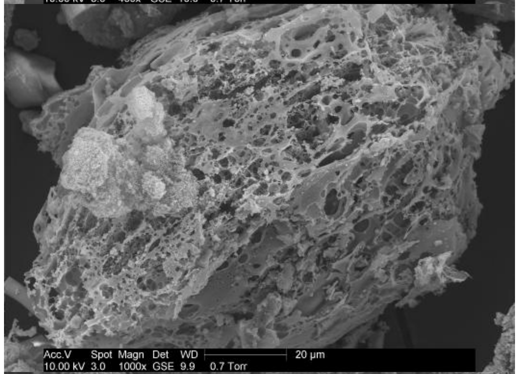


210 ms

MR_{daf} = 87.3%

ρ_p=0.63 g/cc

d/d_0=0.72

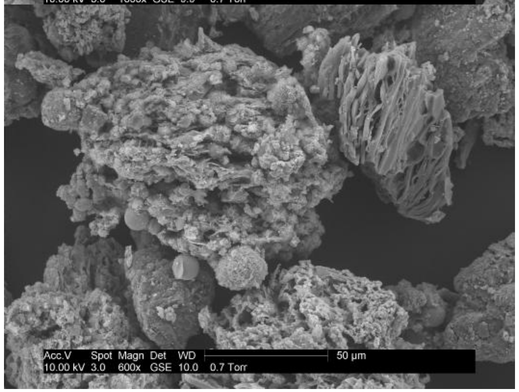


870 ms

MR_{daf} = 90.4%

ρ_p=0.59 g/cc

d/d_0=0.72

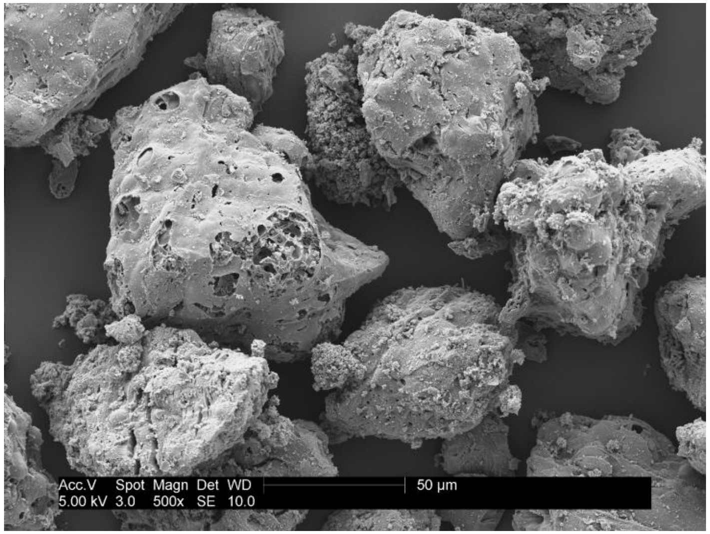


CO_2 Gasification of Wyodak Coal

- Experimental Conditions
  - 2.5 atm, 5 atm, 10 atm, 15 atm
    - Probe set 0.75” above burner
    - 1700 K, Φ=1.24-1.27
  - 5 atm, 15 atm
    - Probe set 3” above burner
    - 1700 K, Φ=1.24-1.27
    - 1900 K, Φ=1.15
  - Fuel mixture
    - 92 mol% CO with H_2
  - Gas composition at 2.5 atm
    - 1.8 mol % H_2O
    - 15.7 mol % CO_2
    - 11.9 mol % CO
    - 0.4 mol % H_2

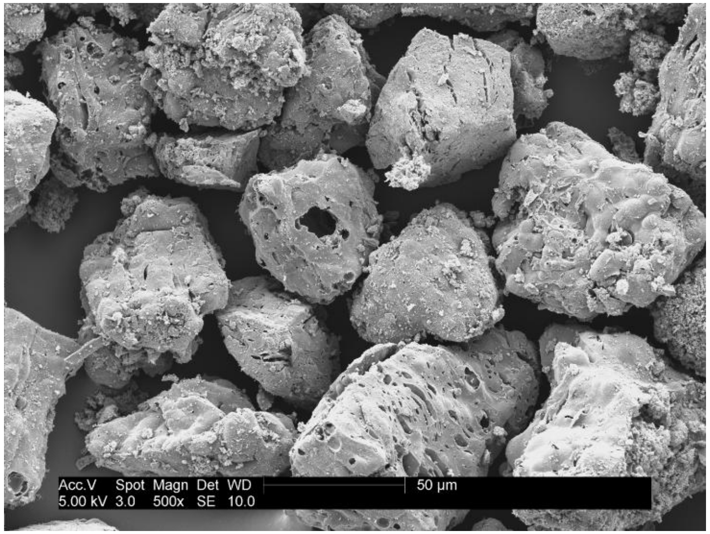
15 atm

44 ms

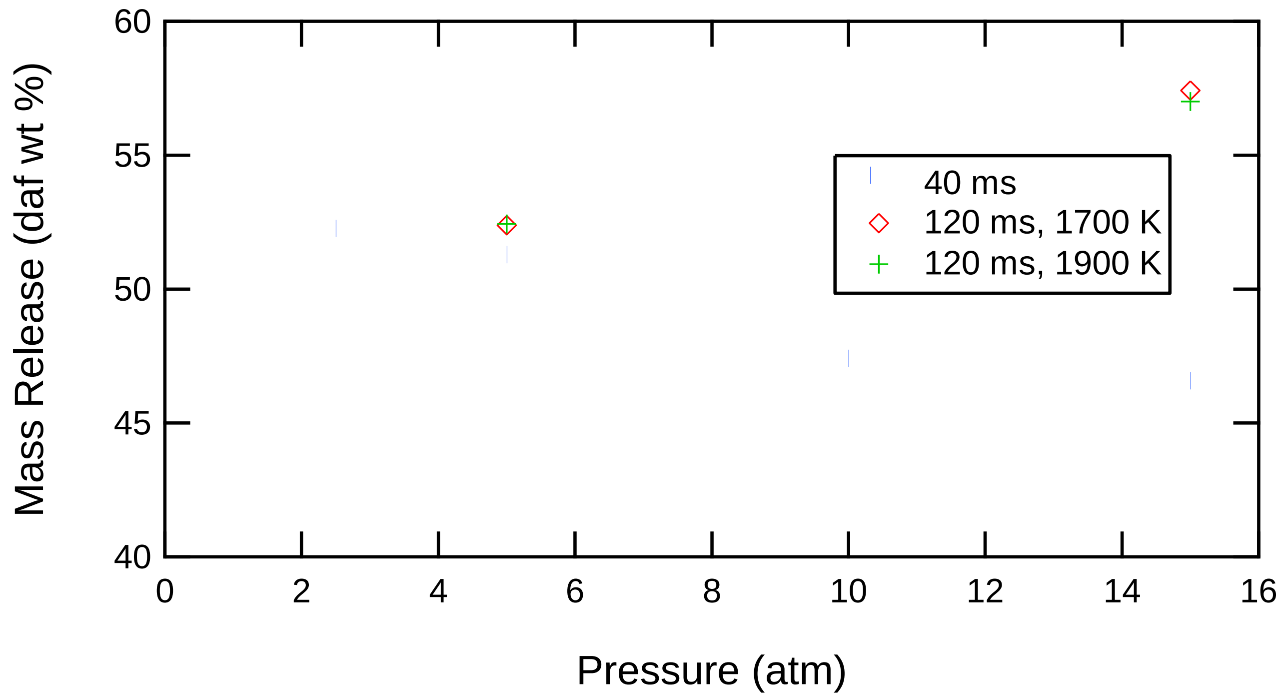


2.5 atm

33 ms

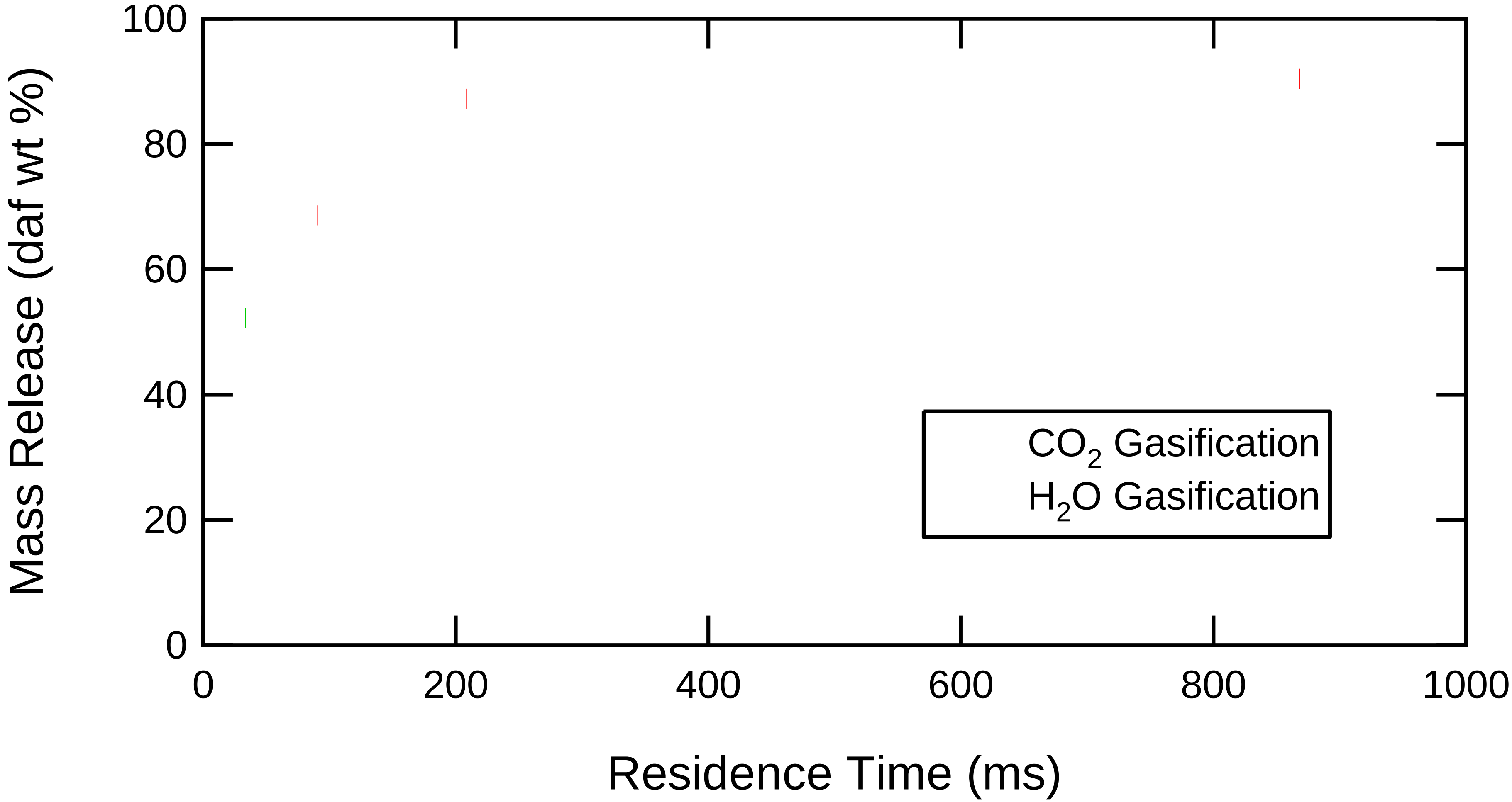


CO_2 Gasification of Wyodak Coal

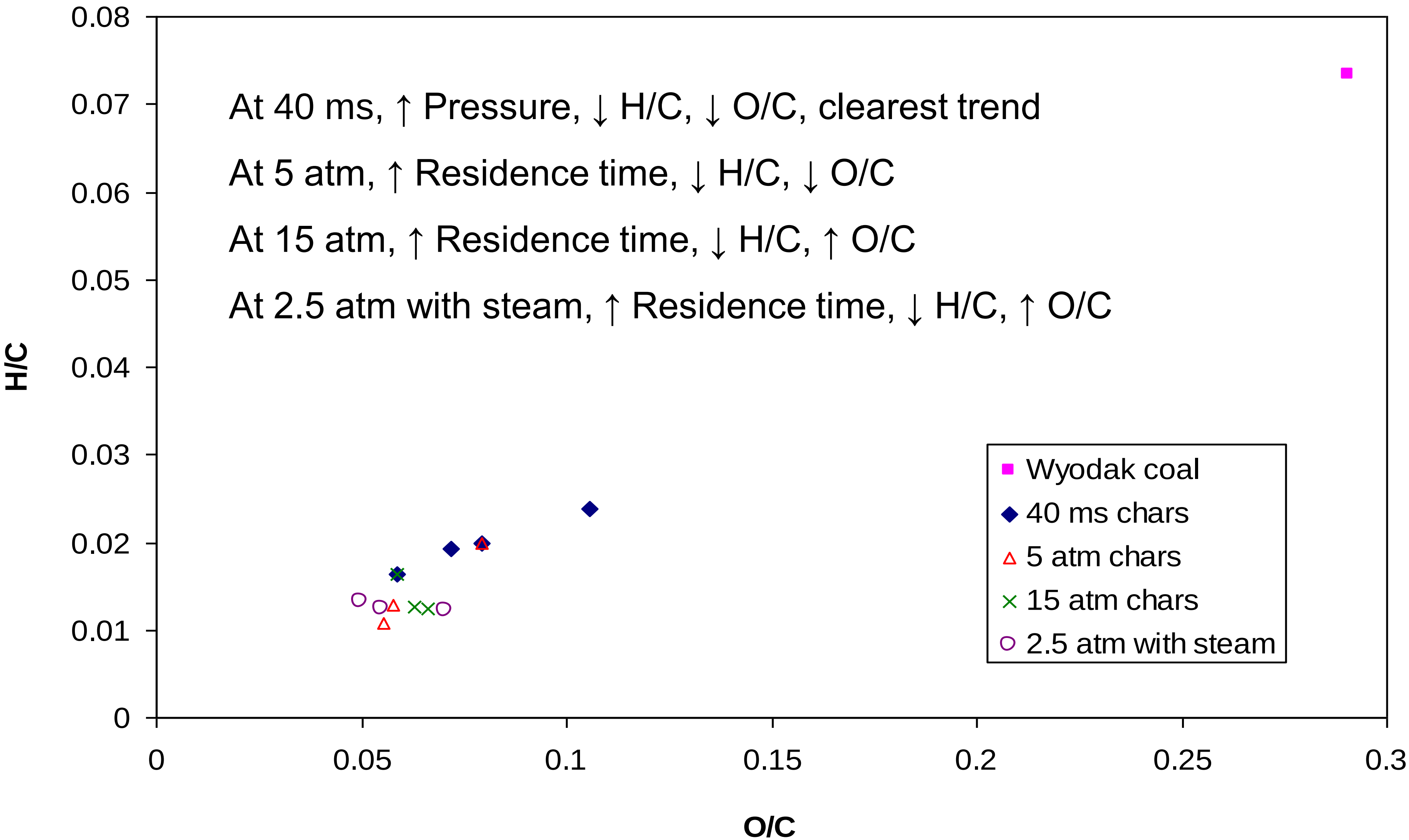


Condition	2.5 atm, 40 ms, 1700 K	5 atm, 40 ms, 1700 K	5 atm, 120 ms, 1700 K	5 atm, 120 ms, 1900 K	10 atm, 40 ms, 1700 K	15 atm, 40 ms, 1700 K	15 atm, 120 ms, 1700 K	15 atm, 120 ms, 1900 K
ρ_p (g/cc)	0.83	0.89	0.91	0.67	0.98	0.93	0.91	0.79
d/d_0	0.91	0.90	0.86	0.96	0.89	0.91	0.89	0.93
Ash Tracer MR (daf %)	46.8	46.6	55.1	60.2	44.5	46.1	50.4	53.9
Average Al/Si Tracer MR (daf %)	52.3	51.3	57.4	57.0	47.4	46.9	52.4	52.4

CO_2 and H_2O Gasification at 2.5 atm, 1700 K

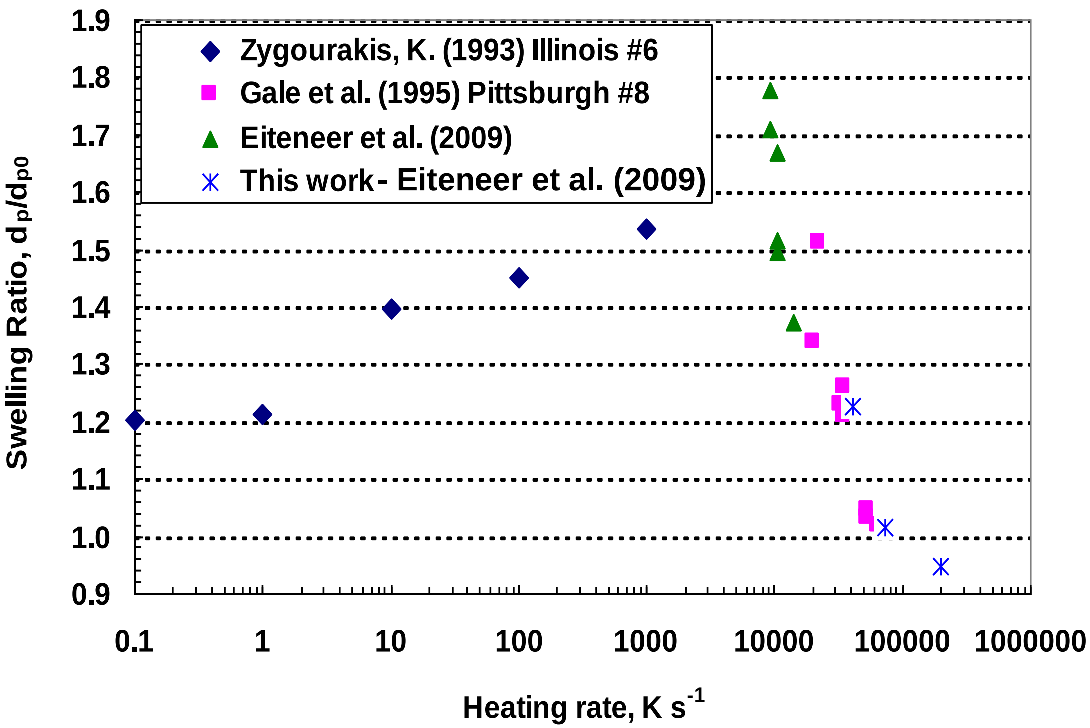


Wyodak Elemental Changes



Atmospheric Swelling

- U.S. bituminous coal
- Atmospheric FFB
  - Varied particle size to change heating rate
- Swelling trends consistent with previous work
  - Sharp decrease between 10^4 -10^5 K/s
  - Apparent asymptote of ~0.9 above 10^5 K/s
  - Eiteneer data indicate maximum swelling occurs slightly below 10^4 K/s



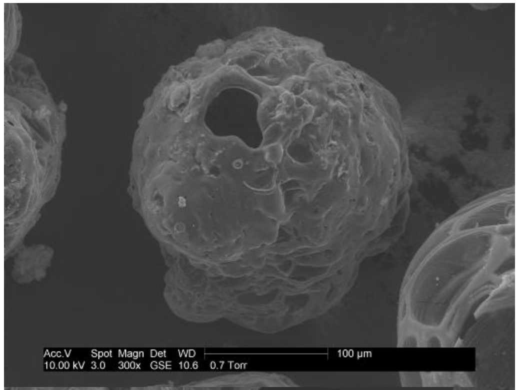
Eiteneer, B., et al., *26th Annual International Pittsburgh Coal Conference*, Pittsburgh, PA (2009).

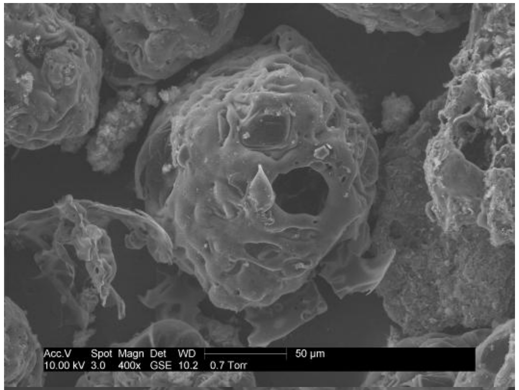
Gale, T. K., C. H. Bartholomew and T. H. Fletcher, *Combustion and Flame,* **100**(1-2), 94-100 (1995).

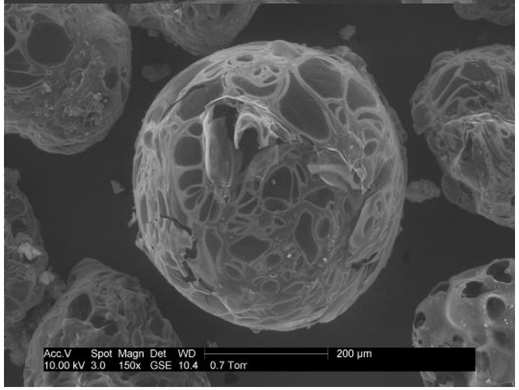
Zygourakis, K. *Energy & Fuels* **7**, 33-40 (1993).

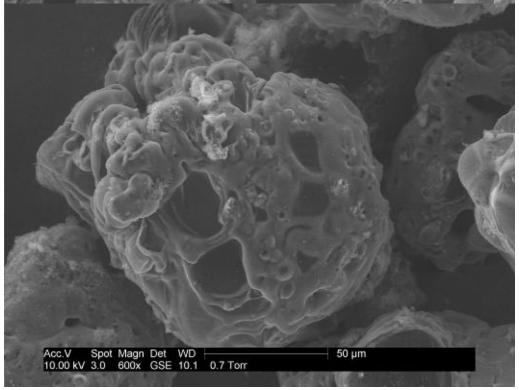
U.S. Bituminous Coal A Swelling

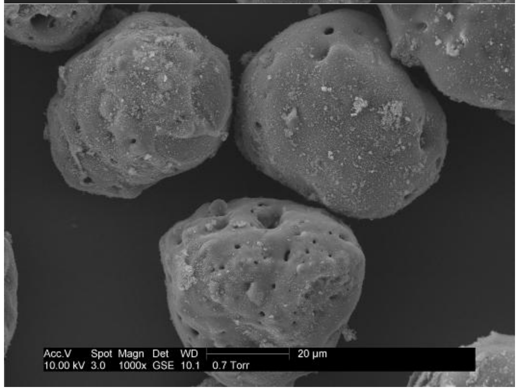
Particle Size (µm)	149-177	88-105	53-66
Heating Rate (K/s)	$4.1 \cdot 10^4$	$7.2 \cdot 10^4$	$2.0 \cdot 10^5$
MR (% daf)	60.29	63.25	61.44
ρ/ρ_0	0.24	0.39	0.53
d/d_0	1.22	1.00	0.93



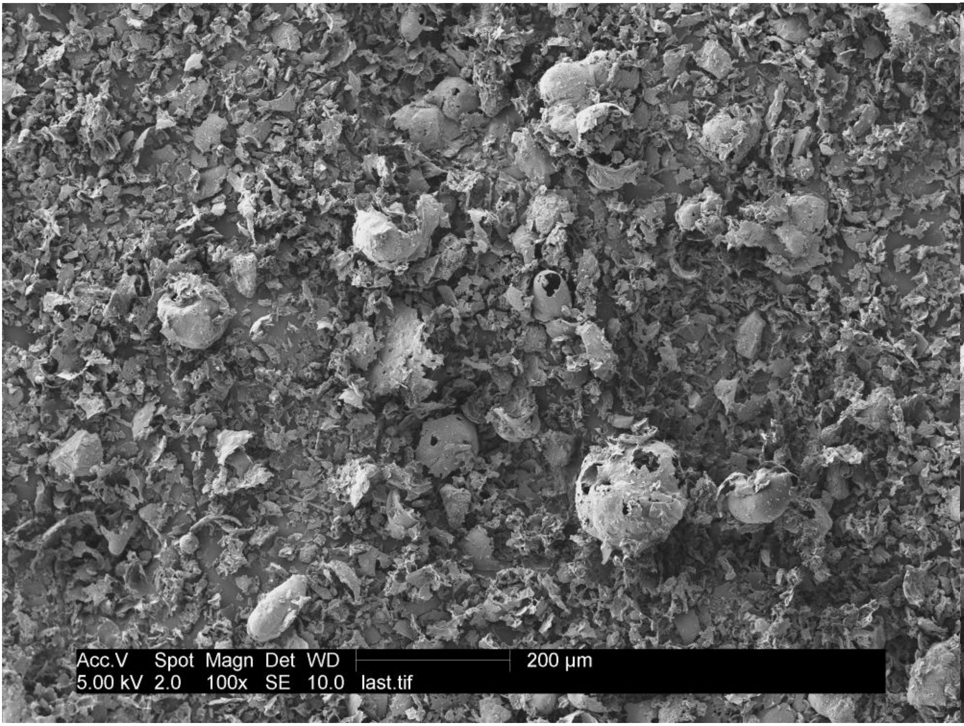




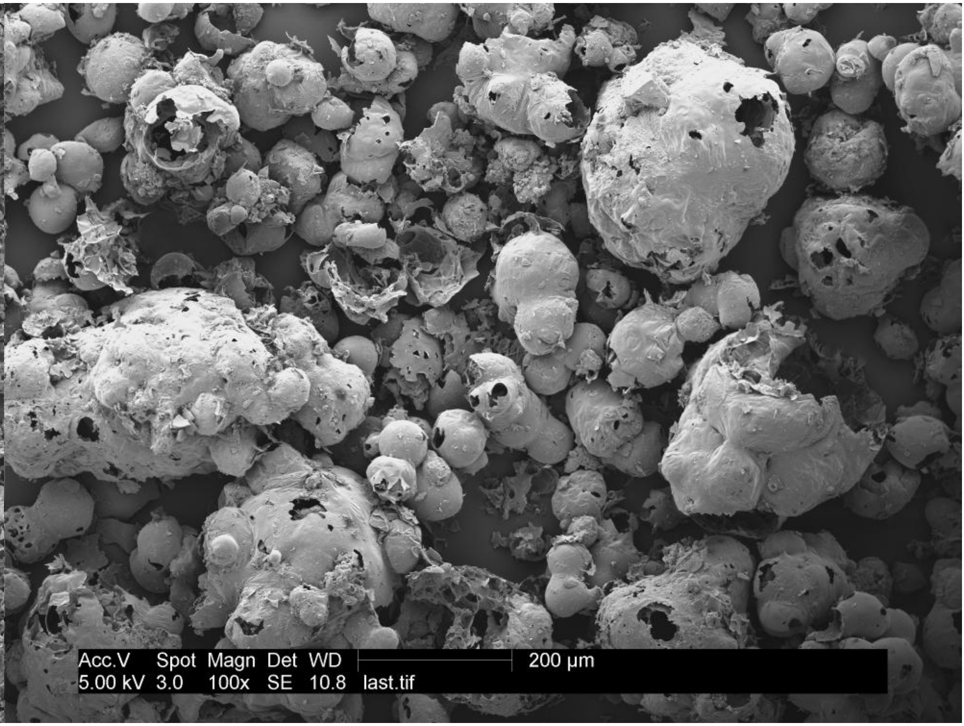




10 atm U.S. Bituminous Coal B

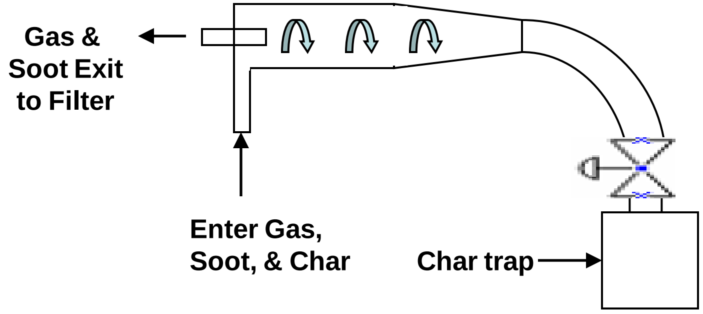


1 gram coal fed



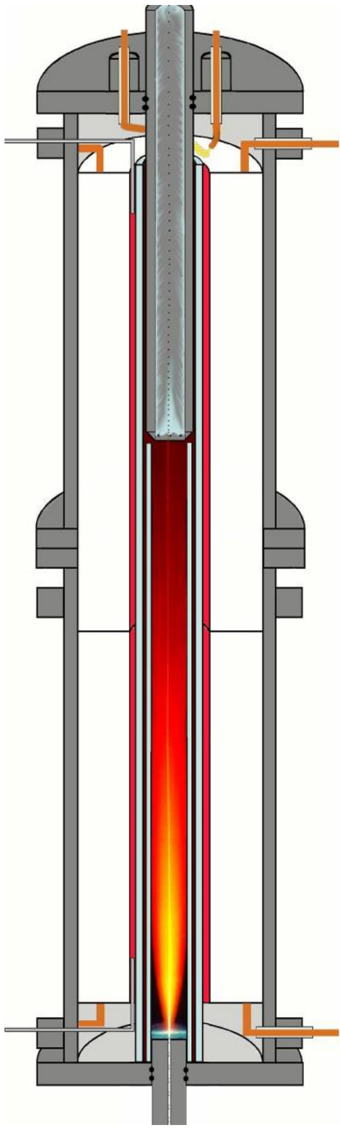
0.5 gram coal fed

- Cenospheric char particles fragile
- Char accumulates in horizontal cyclone
  - Must empty cyclone frequently to avoid fragmentation



Planned Gasification Studies

- Extend HPFFB subbituminous data set
  - Longer RT, multiple temperatures
- Collect HPFFB bituminous coal data
- Determine mass release
  - Compare to CPD code, make adjustments
  - Optimize gasification kinetic parameters
- Measure structural information
  - Determine and model swelling (correlation for CPD)
  - N_2 and CO_2 surface areas
  - Extent of fragmentation
- PTGA gasification kinetics of HPFFB chars
  - Compare kinetics derived from PTGA and HPFFB
    - Make adjustments to gasification model



Summary and Conclusions

- Modified HPFFB suitable for gasification studies
  - Heating rates of ~10^5 K/s at up to 15 atm
  - Gas composition, residence time more flexible
- Preliminary gasification experiments
  - Subbituminous coal in Zone II conditions
  - High surface area and porosity in steam gasification
  - Pyrolysis yield decreases with increasing pressure
- Atmospheric swelling experiments
  - Confirms previous trends
  - Reinforce suggestion of swelling ratio < 1 at heating rates of ~10^6 K/s

Acknowledgments

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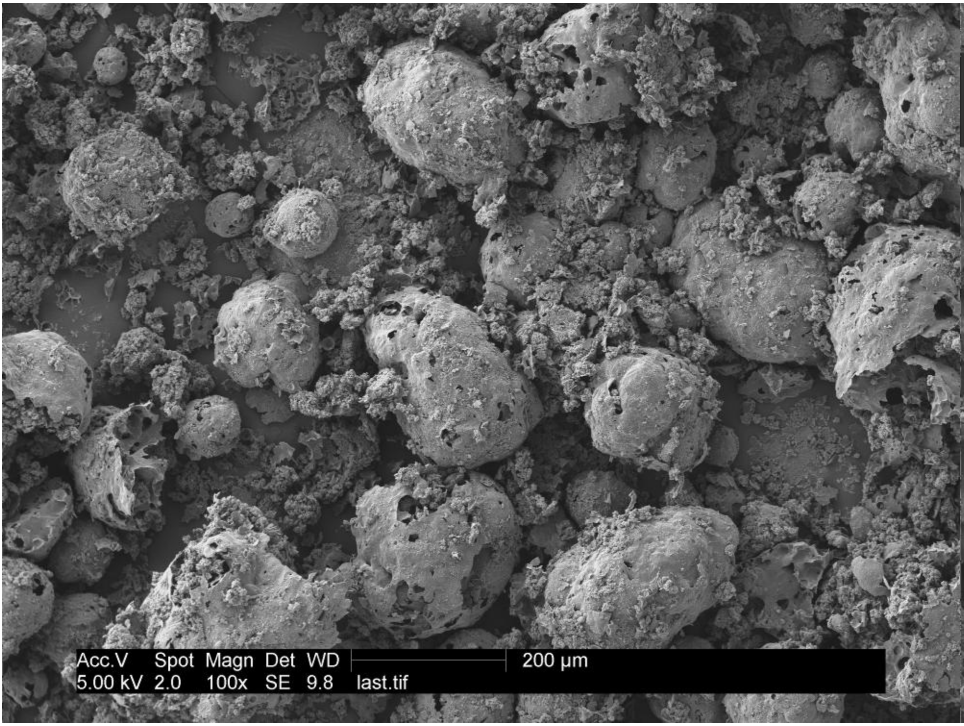
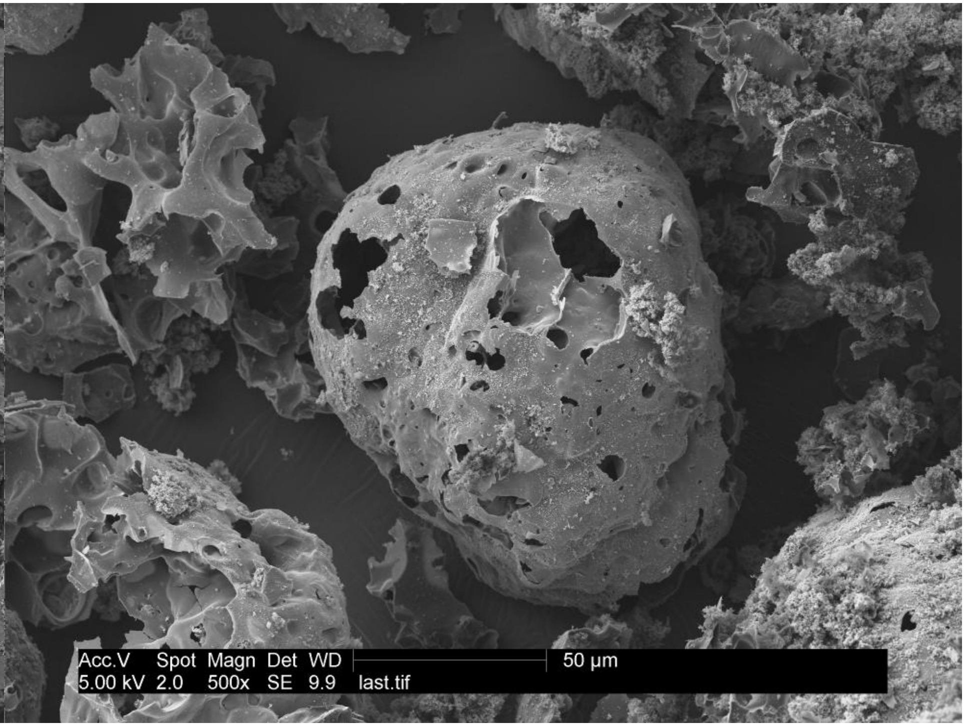
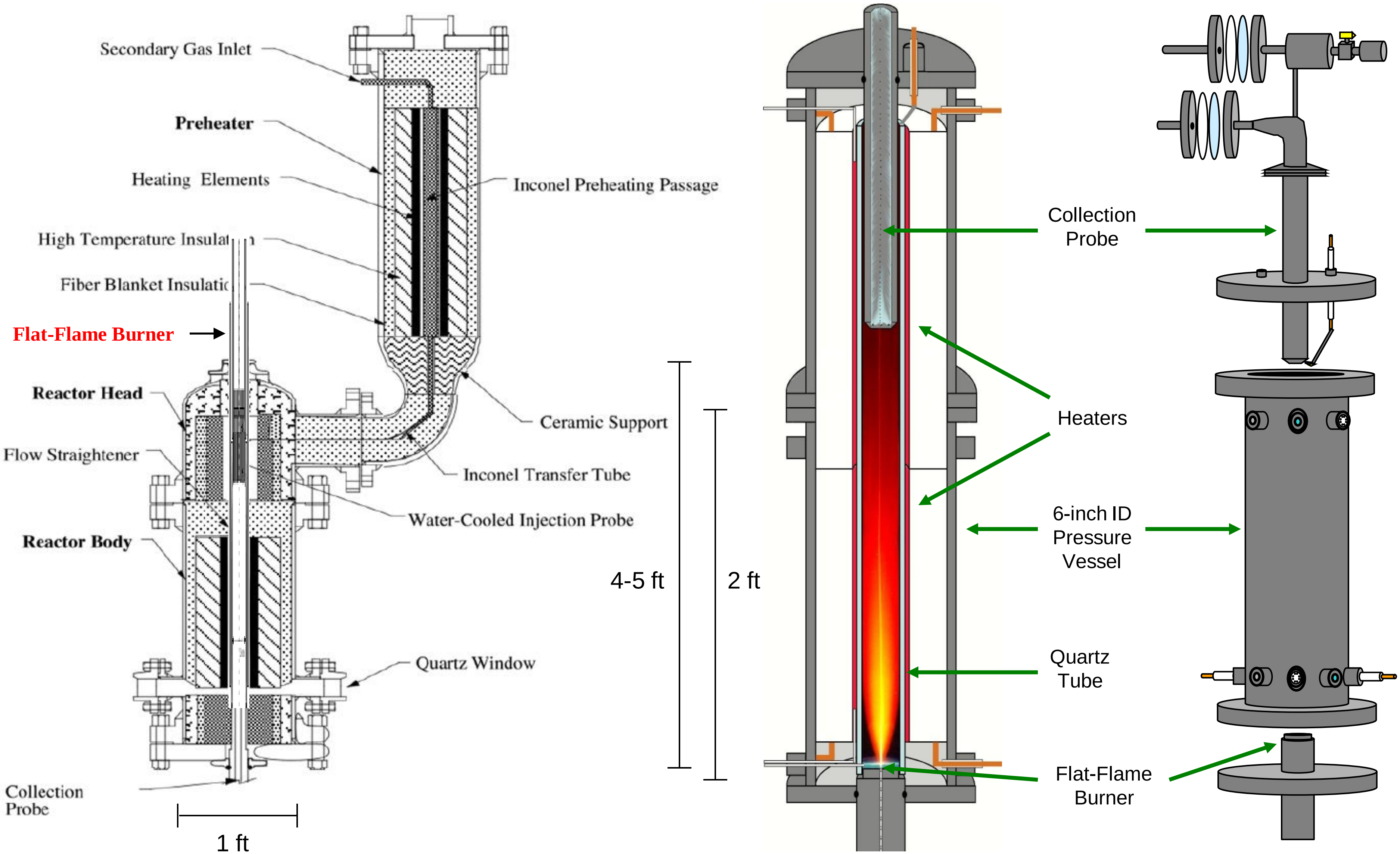
- Undergraduate Research Assistants
  - –Greg Sorensen
  - –Sam Goodrich
  - –Kolbein Kolste
  - –Jeff Van Wagoner
  - –Dallan Prince

15 atm Bituminous Coal B with Soot Agglomerates





BYU HPFFB



Secondary Gas Inlet
Preheater
Heating Elements
Inconel Preheating Passage
Flat-Flame Burner
Reactor Head
Ceramic Support
Flow Straightener
Inconel Transfer Tube
Water-Cooled Injection Probe
Reactor Body
Quartz Window
Collection Probe
1 ft
4-5 ft
2 ft
Collection Probe
Heaters
6-inch ID Pressure Vessel
Quartz Tube
Flat-Flame Burner

Wyodak Ultimate Analysis (daf)

Sample	C	H	N	S	O (diff)
Wyodak Coal	72.25	5.30	0.94	0.50	21.01
2.5 atm 90 ms char (H_2O, 1640 K)	91.14	1.11	1.06	0.27	6.42
2.5 atm 210 ms char (H_2O, 1640 K)	92.50	1.16	0.86	0.39	5.10
2.5 atm 870 ms char (H_2O, 1640 K)	92.69	1.22	0.94	0.53	4.62
2.5 atm 33 ms char (CO_2, 1688 K)	86.99	2.08	1.31	0.44	9.18
5 atm 38 ms char (CO_2, 1714 K)	89.38	1.78	1.33	0.41	7.10
10 atm 41 ms char (CO_2, 1724 K)	90.07	1.73	1.29	0.43	6.48
15 atm 44 ms char (CO_2, 1695 K)	91.38	1.50	1.35	0.41	5.37
5 atm 124 ms char (CO_2, 1714 K)	91.54	1.19	1.40	0.58	5.30
5 atm 110 ms char (CO_2, 1881 K)	91.84	0.98	1.35	0.72	5.10
15 atm 115 ms char (CO_2, 1695 K)	91.26	1.16	1.33	0.50	5.74
15 atm 120 ms char (CO_2, 1953 K)	90.95	1.14	1.26	0.64	6.01