WP AC2 Advanced, high-efficient cycles using GT with sCO_2 or direct oxy-fired CCGT-CCS (WP-AC2 : D1)

and

WP AC1: BECCS – Capture Theme Combined Systems and Capture

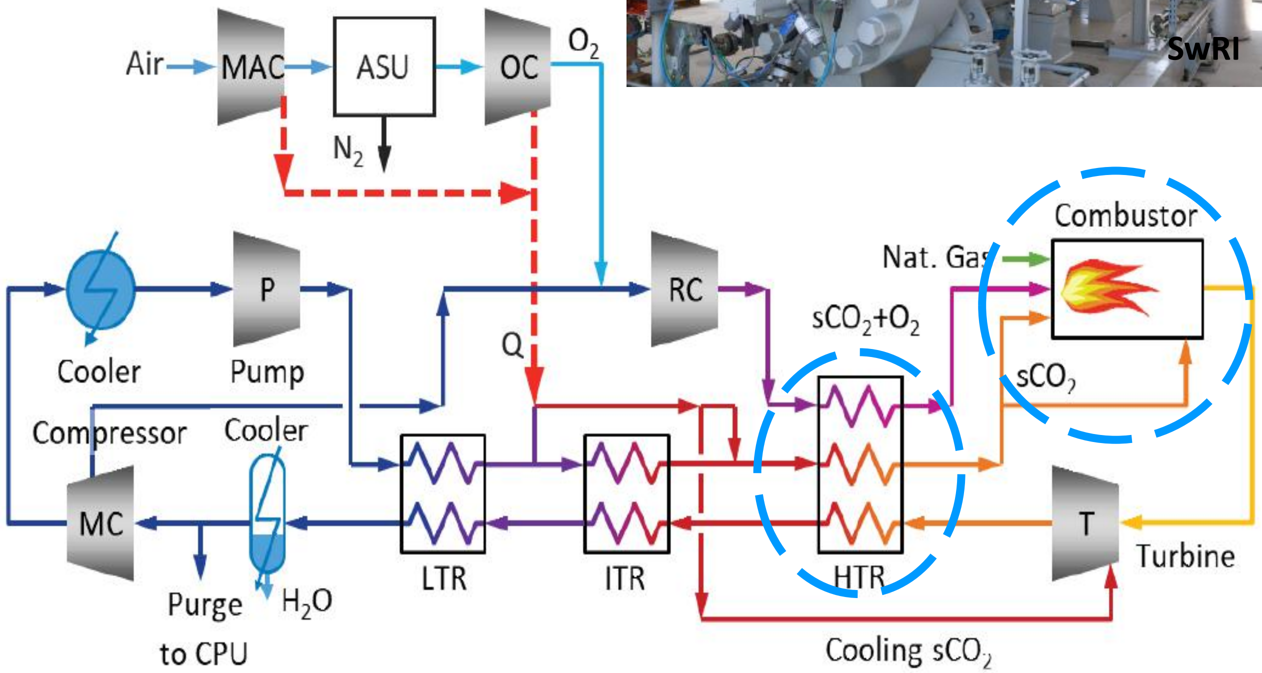
UKCCSRC mid-term review, July 2019

WP AC2: Supercritical Carbon Dioxide Power Cycle for Stationary Power Generation

- **WP AC2:** s-CO2 cycle with oxy fuel HP combustion for improved efficiency and plant flexibility.
  - **Next Generation Technology:** S-CO2/oxy-combustion strategy can be an effective solution for the full integration of Power-to-Gas, CCS, and S-CO2 pumping
  - **Technical Challenges:** Availability of detailed reaction schemes (design the high pressure combustor). validated reaction schemes at HP is subject to many uncertainties.
  - **Deliverables:**
    1. assessing the capability of the available reaction scheme for NG combustion at HP
    2. evaluating kinetic models for both direct fired oxy-combustion and an indirect fired sCO2 energy system
    3. developing a reduced reaction scheme and then integrating with CFD for flow field design.
    4. Evaluating and optimising different cycles to determine combustor design parameters, cycle layout and efficiency, including optimal start and enhanced operational flexibility.

Supercritical Carbon Dioxide Power Cycle for Stationary Power Generation

- Direct-fired sCO2 cycles: high efficiency and integral ability to capture CO2 at HP.
- Reduced inefficiency associated with phase change heat transfer throughout the cycle
- CO2 (working fluid) is non-toxic, and less corrosive than steam
- high cycle pressures, turbomachinery sizes are compact

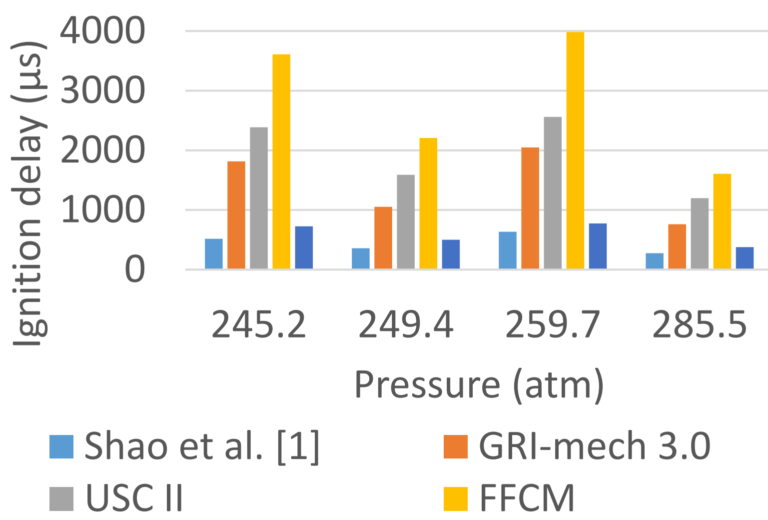


Progress to date: Available validated Chemical Kinetics Reaction Schemes

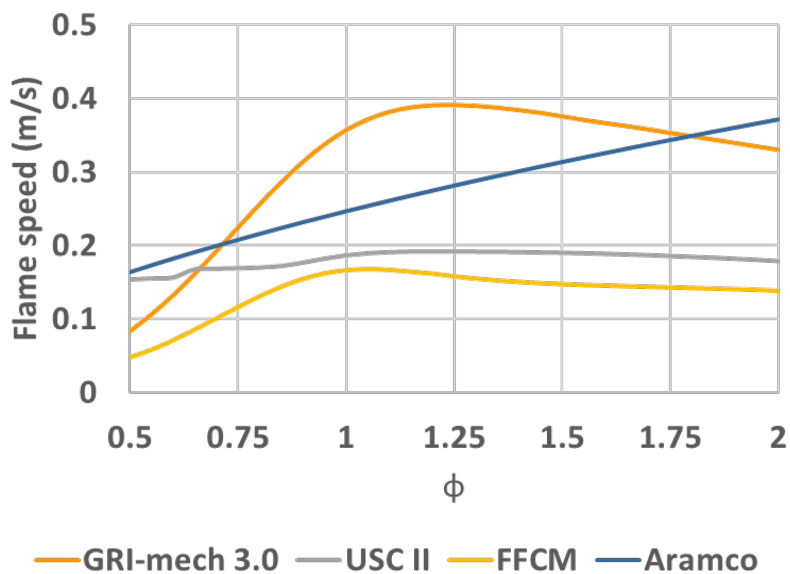
- *Deliverable: assessing the capability of the available reaction scheme for NG combustion at HP*
  - **Aramco Mech V2:** newly developed detailed chemical kinetic mechanism that characterises the kinetic and thermochemical properties of a large number of C1-C4 based hydrocarbon and oxygenated fuels over a wide range of experimental conditions (NUI Galway)
  - **GRI Mech V3.0:**optimized mechanism designed to model natural gas combustion, including NO formation and reburn chemistry
  - **USC-Mech II:** High-Temperature Combustion Reaction Model of H2/CO/C1-C4 Compounds (Southern California)
  - **FFCM Mech:** Foundational Fuel Chemistry Model (Stanford)

Progress to date:
Ignition delay times & Laminar Flame Speed

- Comparison to shock tube data
- IDT = peak OH from Cantera PSR
- Sensitivity analysis on OH formation
  - Both atmospheric and supercritical
- Significant variation in model results



- Cantera Free Flame with ideal gas
- Very significant variation for models
- Similar at atmospheric conditions
- No experimental comparison



Summary of Progress to Date
WP-AC2 : D1

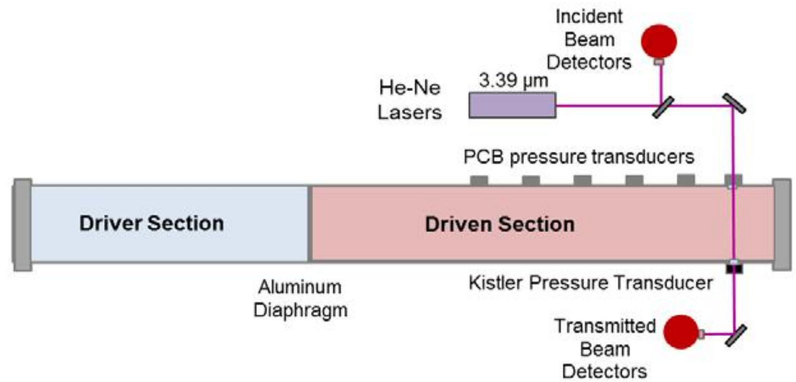
- Section of areas that will be important for computationally modelling the combustor of a sCO2 power cycle has been identified.
- Fundamental properties of the fluid flow would need consideration, and validating
- Heat transfer will require significant analysis, as the pressure- path-length of the combustor will result in significant radiative heat transfer through the combustion medium, however it is unclear what the impact will be at real combustor length-scales and environments.
- The nature of the underlying chemistry is also likely to require significant validation.
- flame speed and species profiles need further validation, as there are significant variations in the current models.

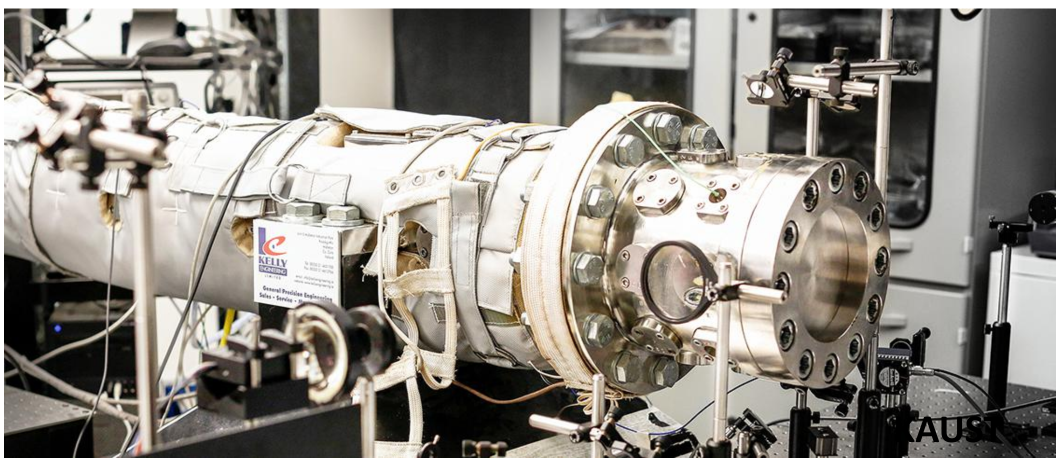
WP-AC2 : D1 Future Plan

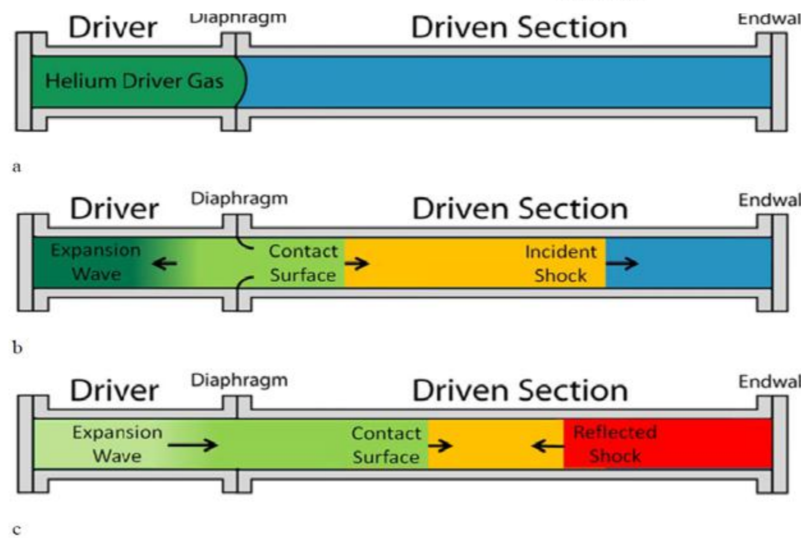
sCO2 Combustion: Technology Challenges

High Pressure Shock Tube Studies of O2/CH4/CO2 Combustion

- **Shock tube/laser absorption strategies are well-suited kinetics studies and ignition delay process.**
- **Shock Tube measurements can be used to make new chemical kinetic models and evaluate the accuracy of existing chemical kinetic models**







WP-AC2 : D1 Future Plan

sCO2 Combustion: Technology Challenges

- We are building a heated high-pressure shock tube capable of operating at pressures of up to 270 atm and supercritical het exchanger test bed to study:
  - Ignition behaviour of a large range of fuels at high pressure
  - Chemical kinetics of various fuels (fuel flexibility) under homogeneous conditions of temperature and pressure
  - Measurements of stable intermediates during fuel pyrolysis
  - Ignition delay times will be measured at high pressure in the gas-phase for several fuels in various oxidizers behind reflected shock waves
  - Heat transfer mechanism at sCO2 system
  - Available from 01/2021.
- **PACT Welcomes Contribution/collaboration/partnership on developing sCO2 Carbon Dioxide Power Cycle for Stationary Power Generation**

WP AC1: BECCS – Capture Theme (Combined Systems and Capture)

INTRODUCTION

- BECCS – bioenergy coupled with carbon capture and storage – is critical for achieving UK and global CO_2 reduction commitments, with much previous research demonstrating the importance of practical trials to build industrial confidence in the technology
- Here, pilot-scale testing at PACT is assessing air- and oxy-combustion of a range of fuels, including:
  - North American Grade A white wood
  - short-rotation coppice (SRC) willow
  - Grade A recycled (waste) wood from clean pallets

WP AC1: BECCS – Capture Theme (Combined Systems and Capture)

OBJECTIVE

- To identify key species and pollutants from combustion and evaluate their impacts on solvents and capture plant operation, with:
  - extensive analysis of combustion gases (through FTIR)
  - assessment of entrained metal aerosol release (via ICP-OES)
  - an examination of submicron particulate matter formation, including online particle size and concentration (using DMS)

Gasmet DX4000 FTIR analyser

Spectro CIROS^{CCD} ICP-OES

Cambustion DMS500

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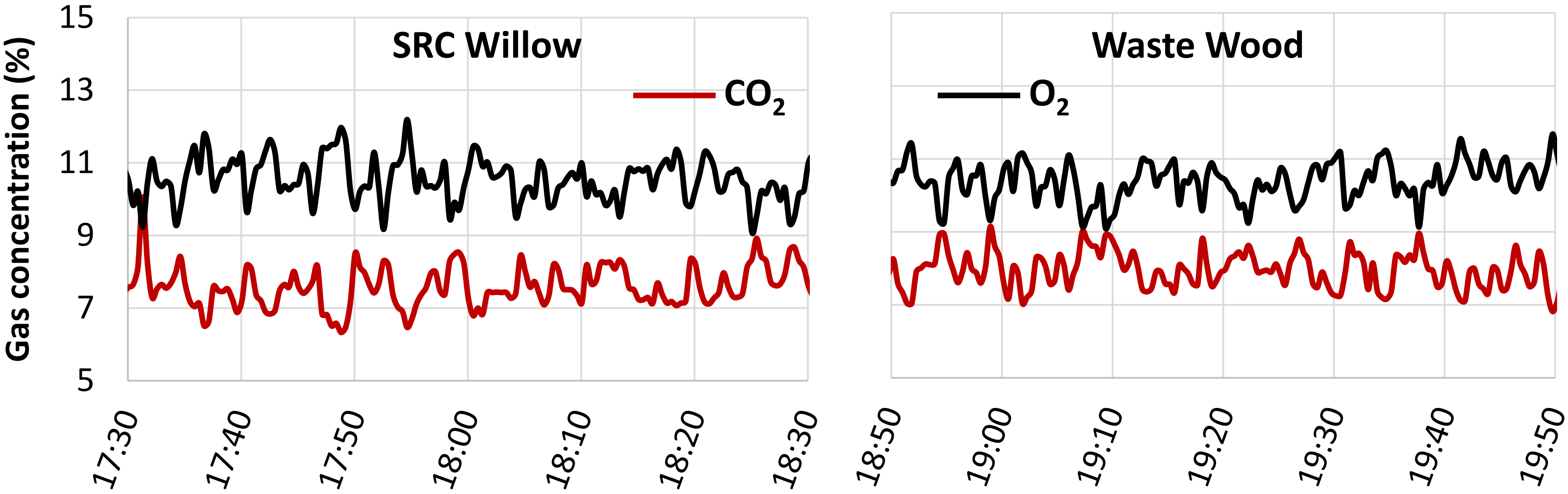
COMBUSTION GAS ANALYSIS

	SRC Willow	Waste Wood
CO_2 (vol%)	7.6	7.9
O_2 (vol%)	10.5	10.4
H_2O (vol%)	9.7	10.1
CO (ppm)	233	174
NO (ppm)	114	77
SO2 (ppm)	21	17
HCl (ppm)	0.04	0.02



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ENTRAINED METAL AEROSOL RELEASE

	SRC Willow	Waste Wood	White Wood
Key Elements in Fuel	Ca, K, Zn	Ca, Fe, K, Mg, Na, Zn	Ca, K, Mg, Zn
Combustion Type	grate-fired	grate-fired	pulverised
Key Elements as Aerosols	K, Zn	Al, Fe, K, Pb, Zn,	K

- Key findings:
  - K emissions from SRC willow were much greater than for waste but average levels of Pb/Fe from the waste were significantly higher than for the willow
  - Hg aerosols were not detected for either flue gas, with low levels of other heavy/toxic metals (As/Cr/Cd) were observed
  - There was considerable temporal variation in the metal levels released from the waste due to its heterogeneous nature
  - The waste wood had greater levels of transition metals that can negatively impact capture solvents through initiating/catalysing oxidative degradation
  - Oxy-fuel combustion released much greater levels of metals in the gas-phase compared to air-firing due to the variations in the operating conditions and in-furnace environment (combustion/oxidising regime)

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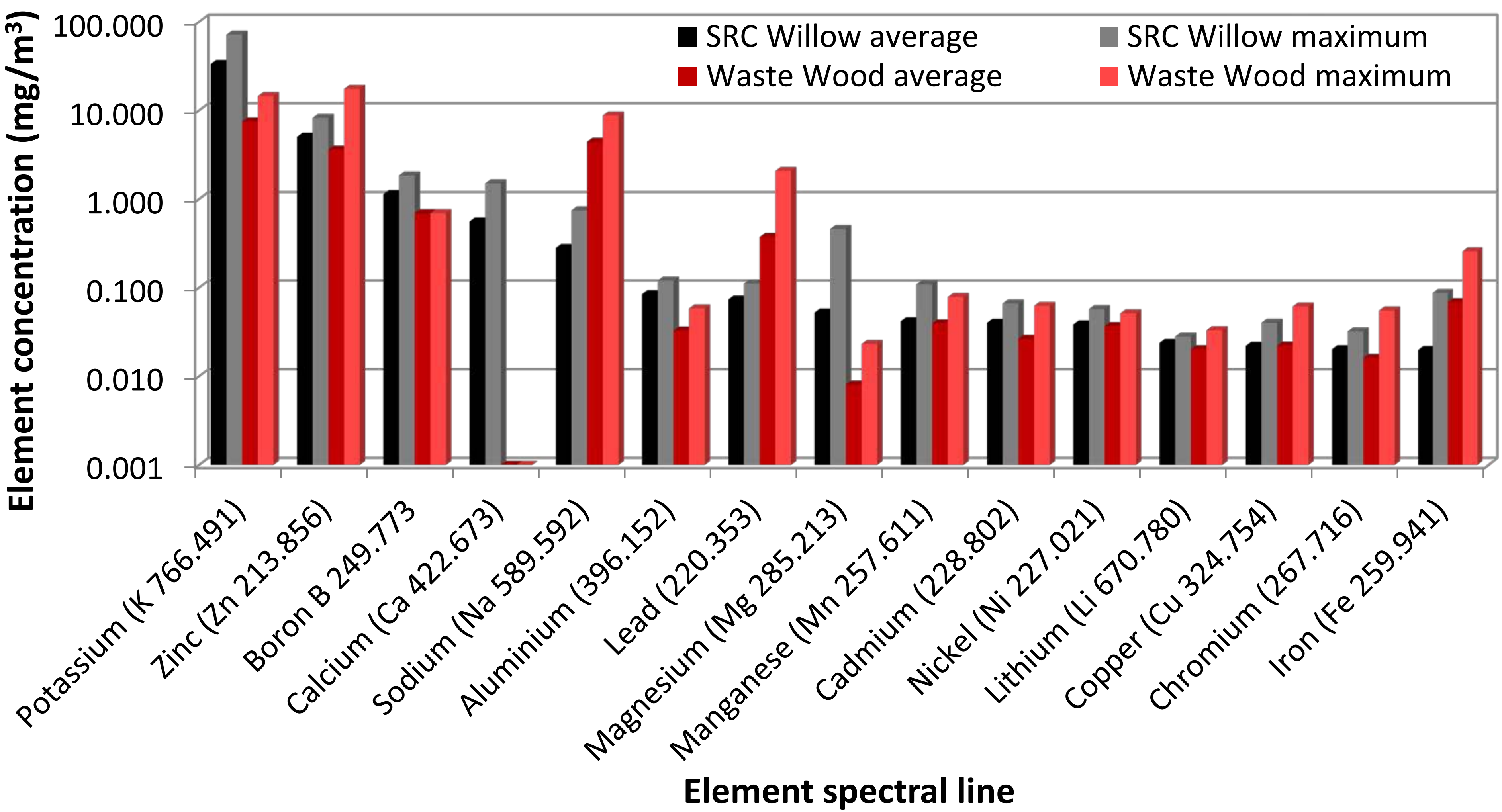
ENTRAINED METAL AEROSOL RELEASE



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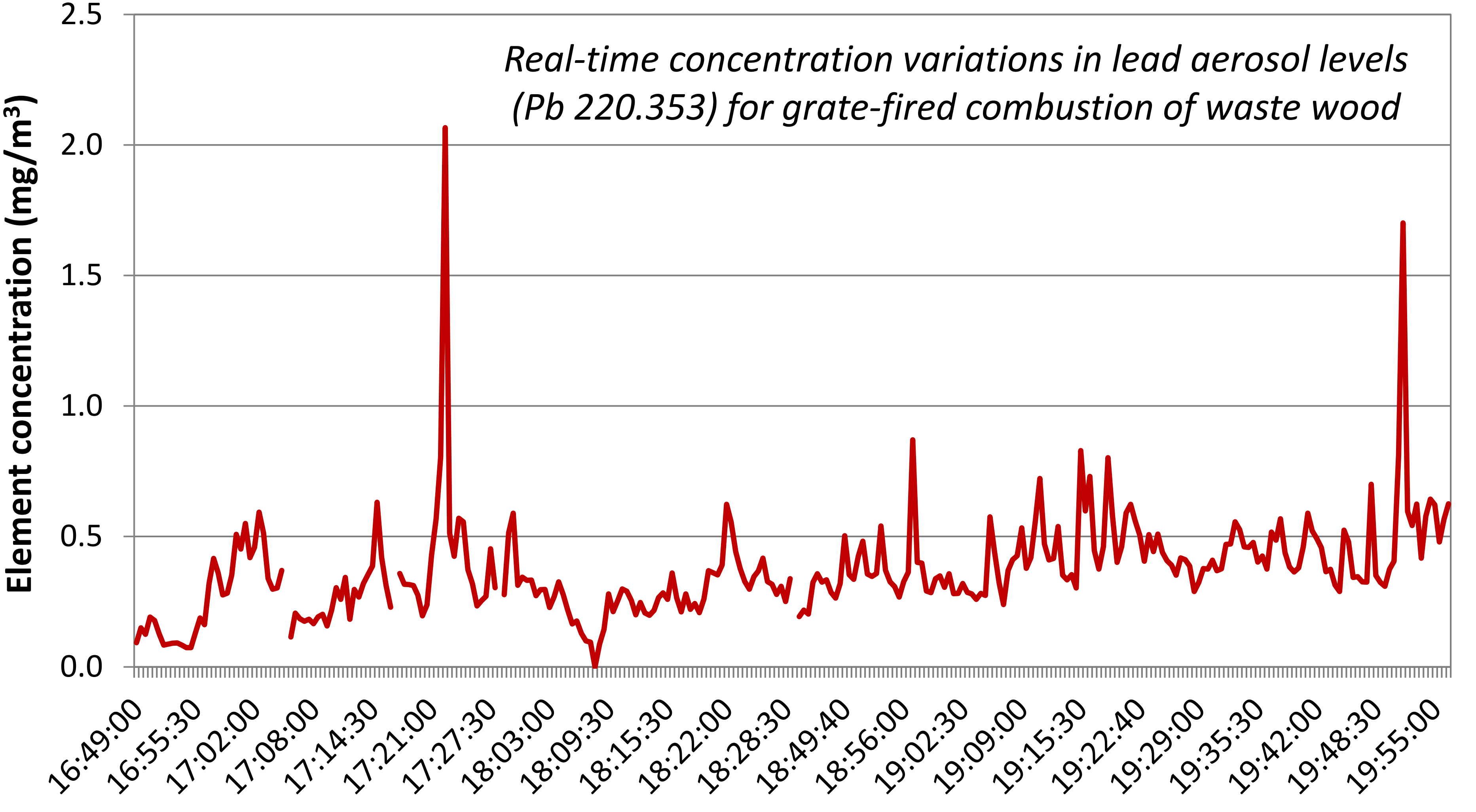
REAL-TIME ENTRAINED METAL AEROSOL RELEASE



WP AC1: BECCS – Capture Theme (Combined Systems and Capture)

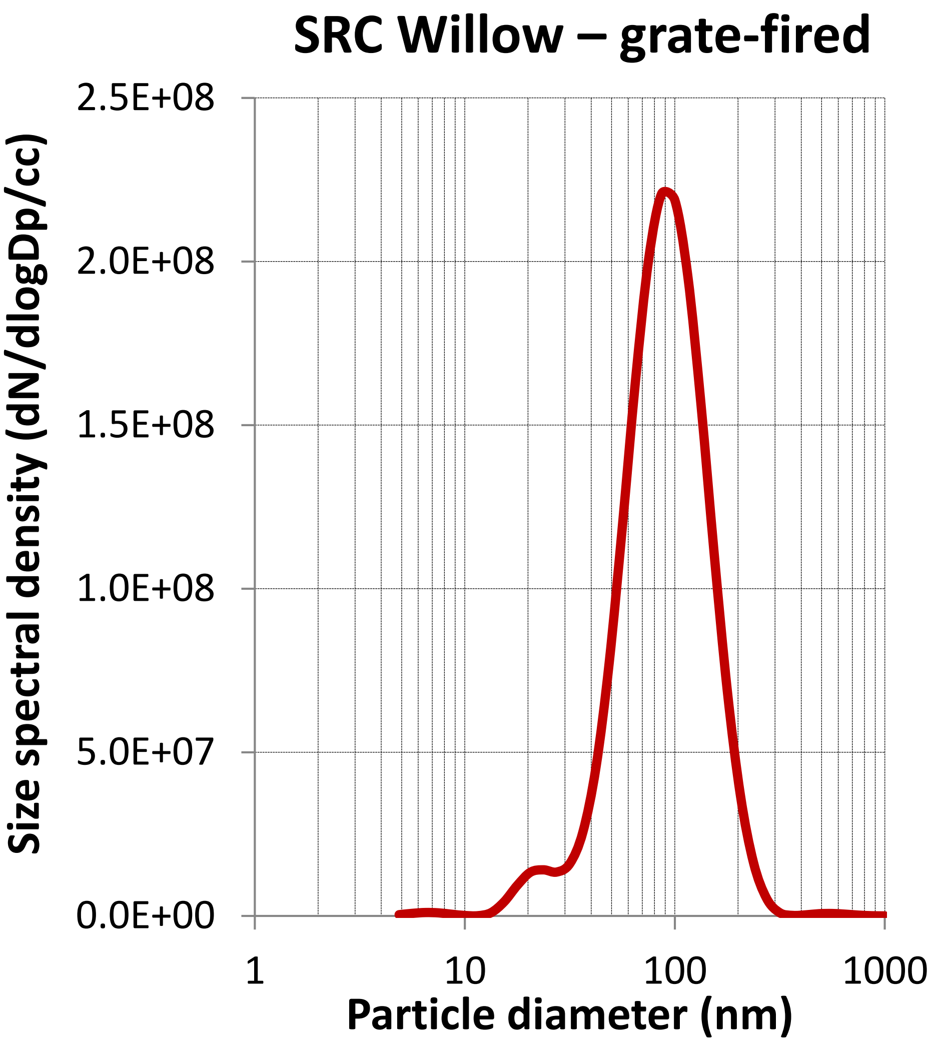
SUBMICRON PARTICULATE MATTER

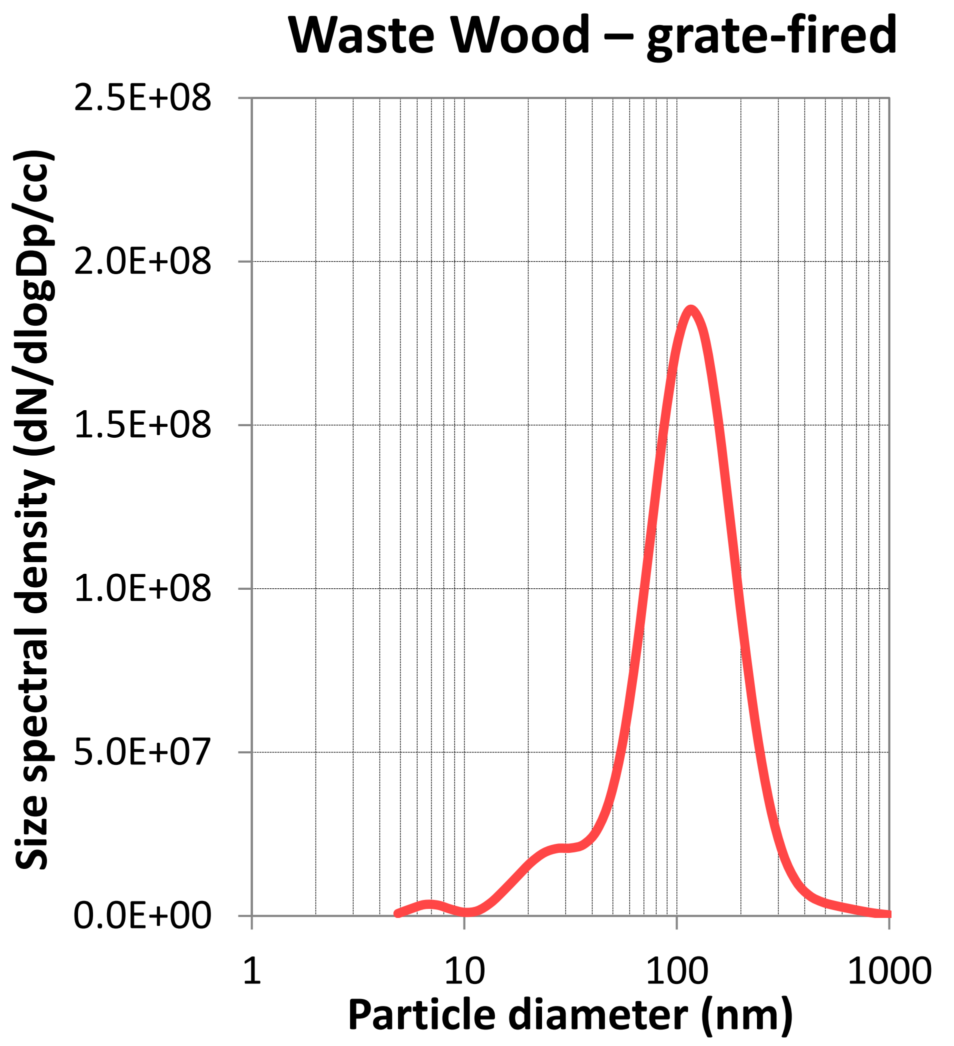
	SRC Willow	Waste Wood
Total (N/cc)	107,637,062	102,449,915
Geometric Mean Diameter (nm)	86.54	103.03
Geometric Standard Deviation of Diameter	1.66	1.95
Count Median Diameter (nm)	89.59	111.18

- Key findings:
  - The waste wood had a slightly lower total particle concentration
  - The SRC willow had smaller particles present on average
  - Due to the differences in gas cleaning between the grate-fired and pulverised burners, grate combustion released many more submicron particles, which can also negatively impact capture performance
  - Although ash fusion temperatures were similar, the initial deformation and softening temperatures were lower for the waste wood, indicating more deposition may occur

WP AC1: BECCS – Capture Theme (Combined Systems and Capture)

SUBMICRON PARTICULATE MATTER

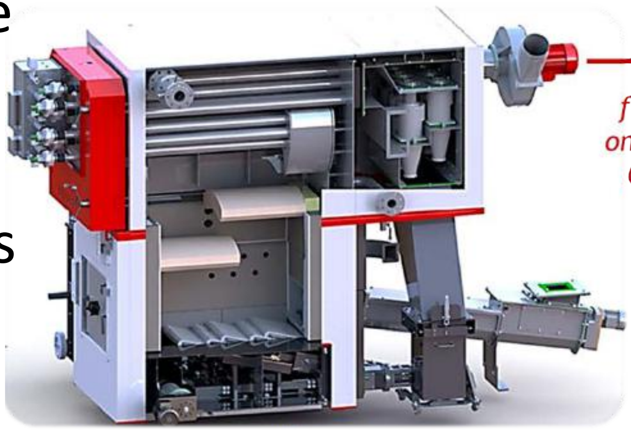




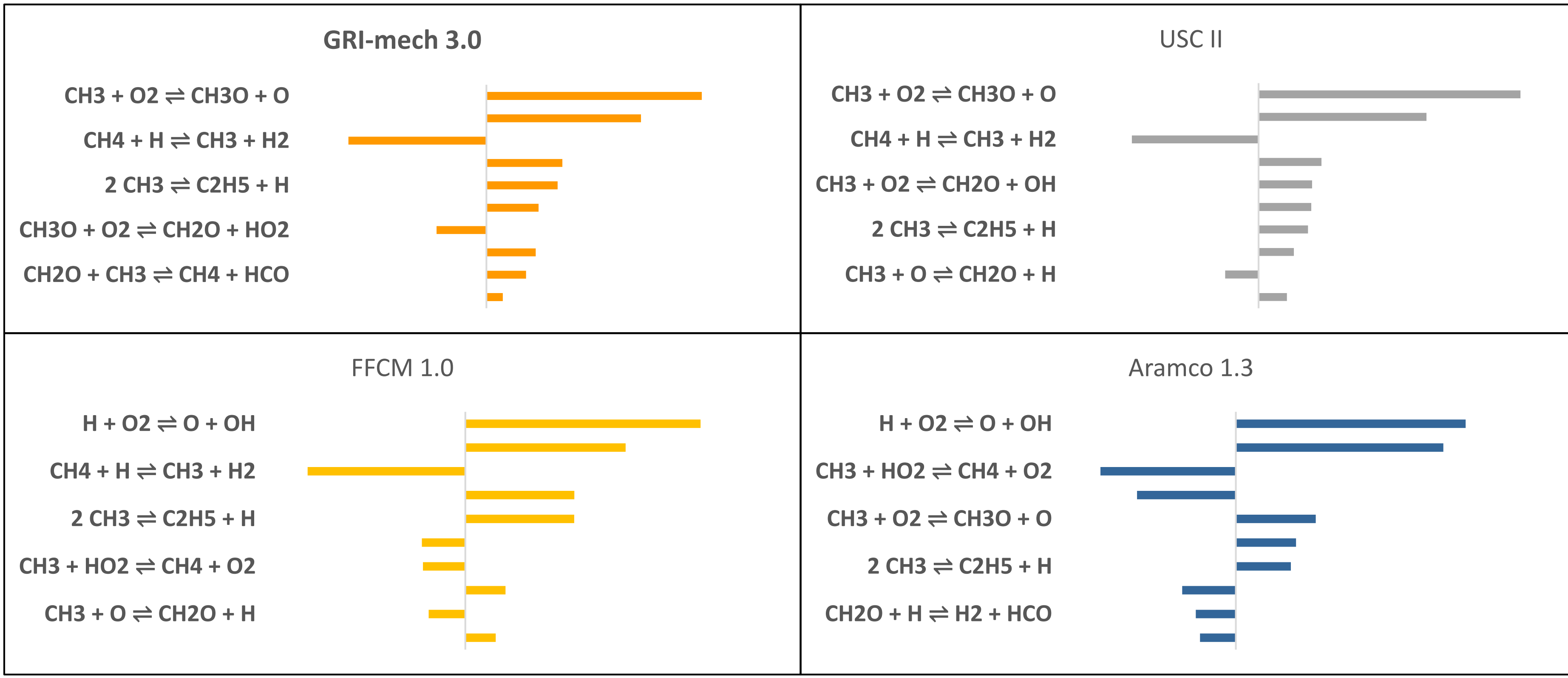
WP AC1: BECCS – Capture Theme (Combined Systems and Capture)

NEXT STEPS

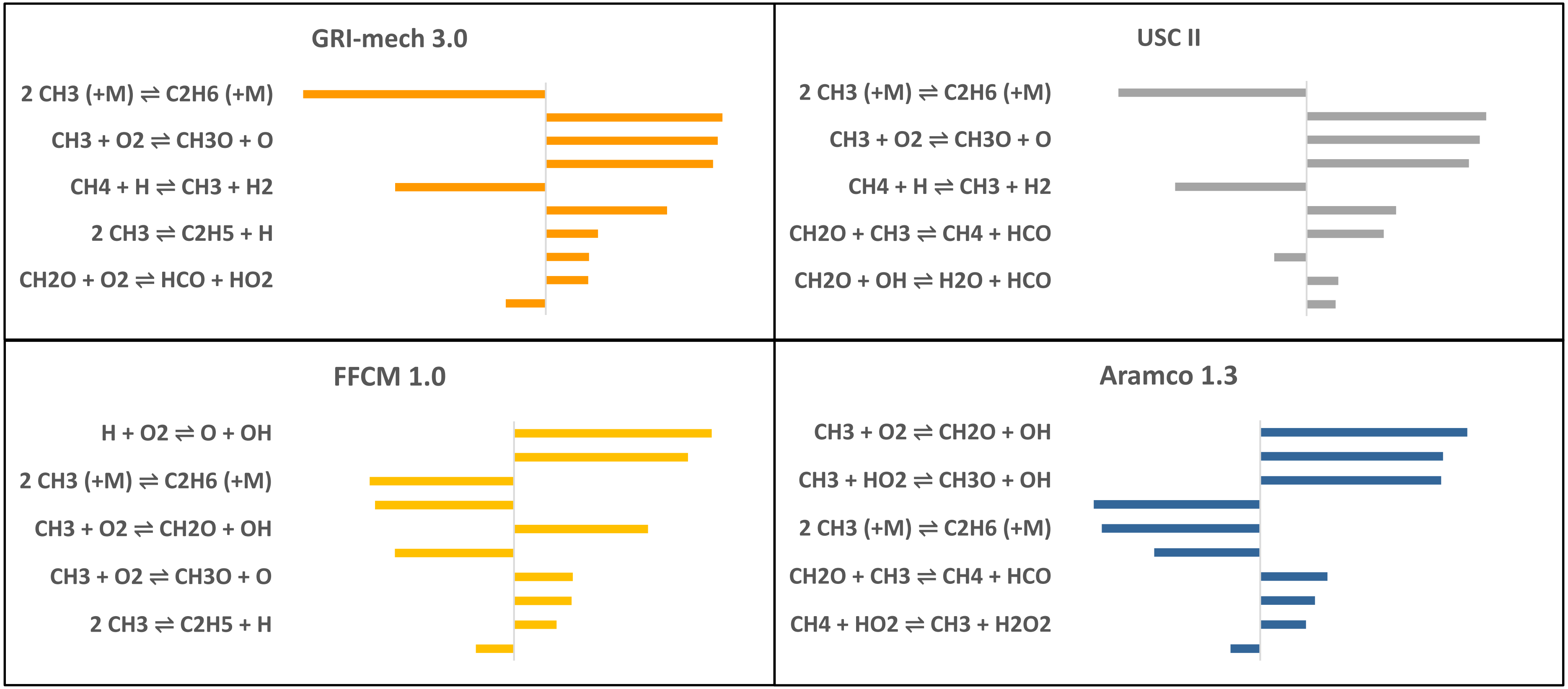
- Full integration of combustion and capture plants, to assess impacts of alkali/transition/heavy metals on: (i) oxidative solvent degradation; (ii) corrosion of capture solvents; and (iii) contamination of high-purity CO_2
- Focus on wastes and more contaminated fuels with higher concentrations of trace elements that can be detrimental to solvent integrity and plant performance; further research at PACT will provide valuable data on operating CCS under waste-to-energy conditions



Sensitivity at atmospheric pressure



Sensitivity at supercritical pressures



Sensitivity analysis

- Sensitivity analysis on ignition based on OH
- Calculated reaction sensitivity as $S_k = \max\left(\frac{k_r}{y_{OH}} \frac{\delta y_{OH}}{\delta k_r}\right)$
- Sensitivity calculated for:
  - T_0 = 1100 K, P=1 atm, CH_4: 7.5%, O_2: 15%, CO_2: 77.5%
  - T_0 = 1100 K, 285 atm , CH_4: 7.5%, O_2: 15%, CO_2: 77.5%