ADVANCES IN »
HYDROTHERMAL CONVERSION OF INDUSTRIAL BIOGENIC RESIDUES INTO INTERMEDIATE BIOENERGY CARRIERS

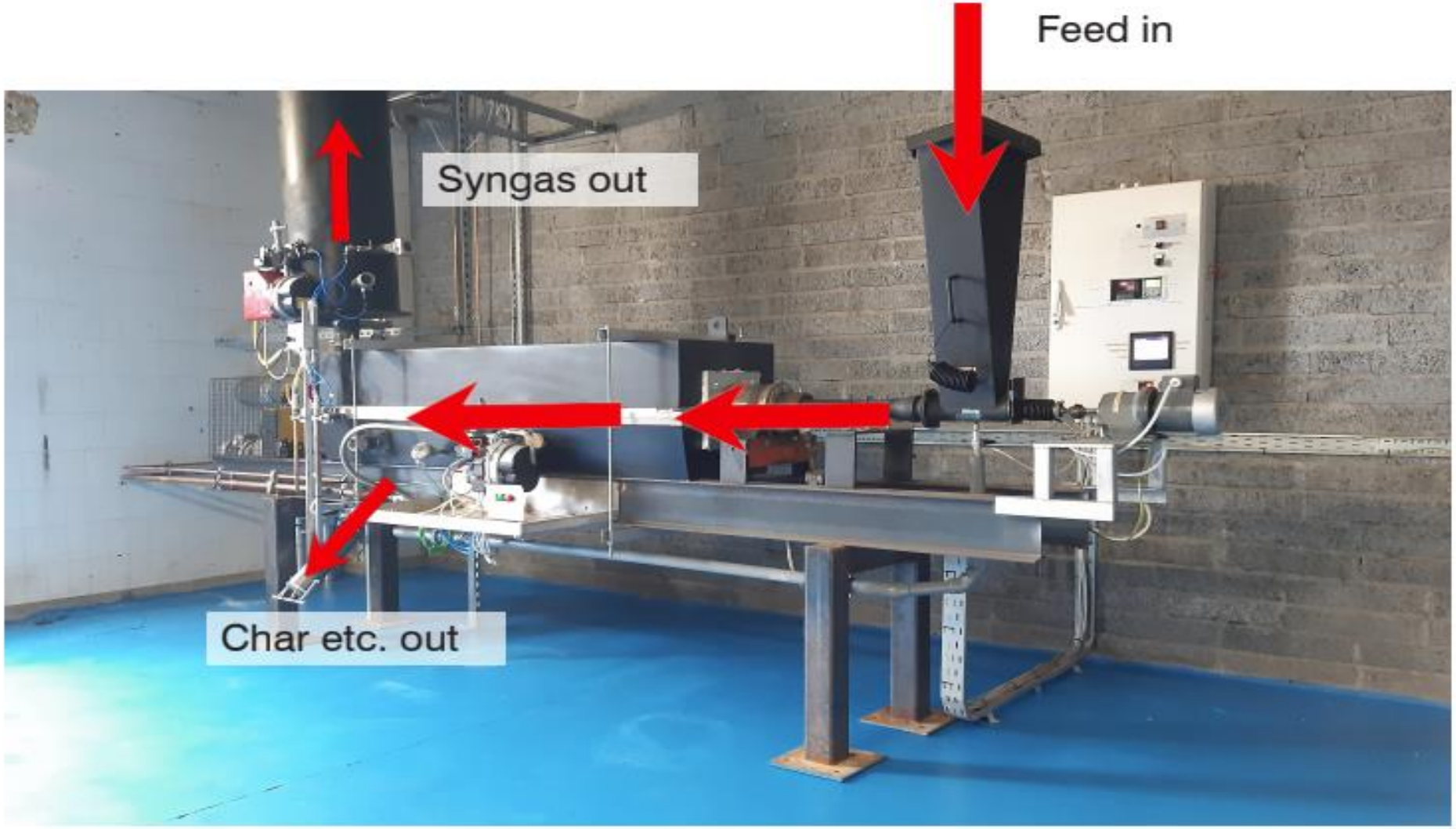
RESULTS FROM THE **F-CUBED PROJECT**

F-CUBED

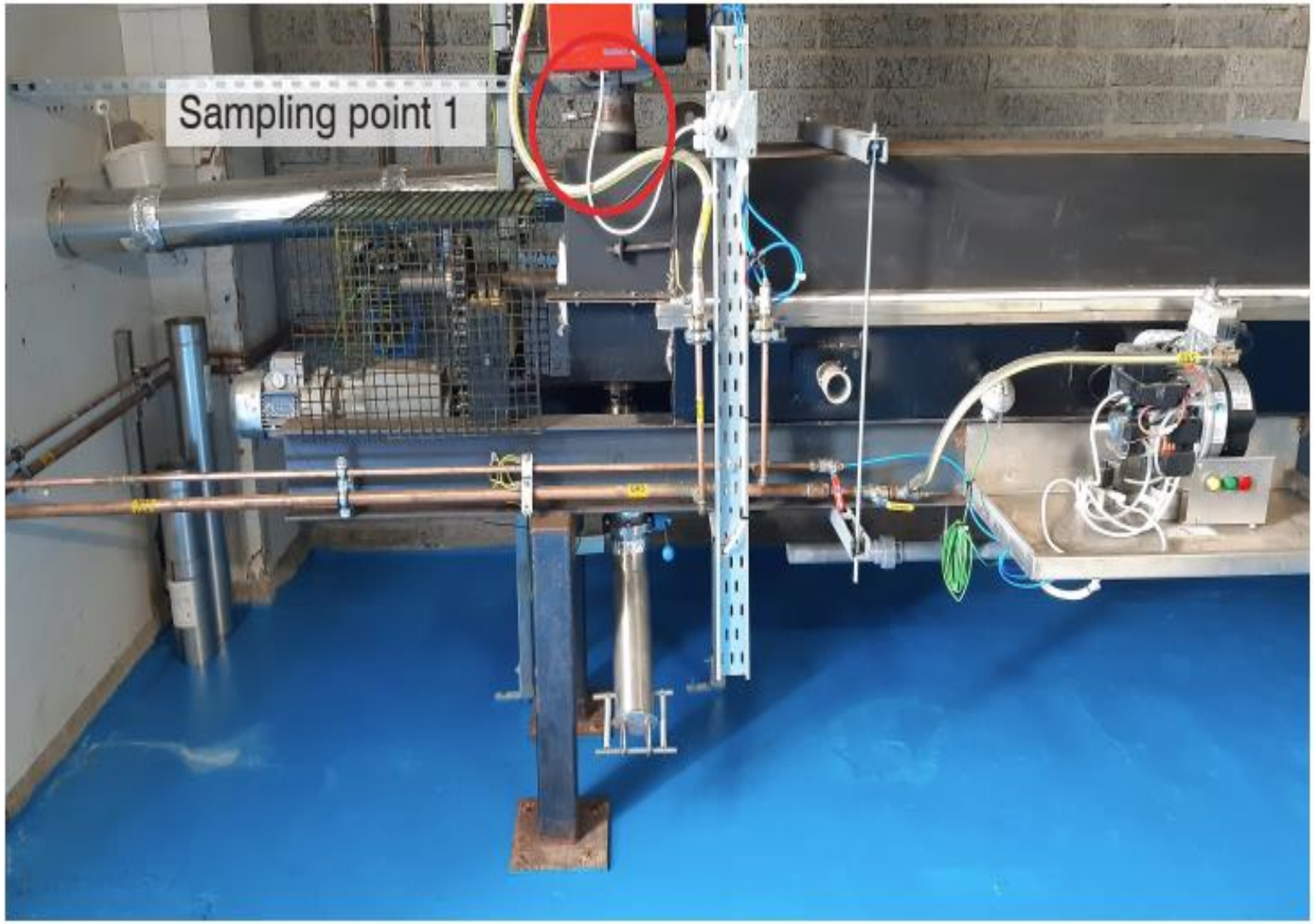
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 884226.

Combustion and Gasification of Pellets produced from TORWASH®

Material Flow Overview



Sampling pt 1 – Syngas (pre-combustion)



Note: Sample point and valve was later increased to DN40

Sampling pt 2 – Off-gas (post-combustion)

Note: Afterburner is also internally insulated

Temperature Probe Locations

Internal Bed Temp Measurement (i.e. Kiln Process Temp)

Discharge Temp Measurement

Temperature Probe Locations

T1 Temp Measurement (i.e.Combustion Chamber Temp Measurement opposite the burner)

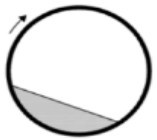
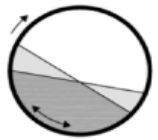
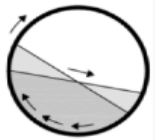
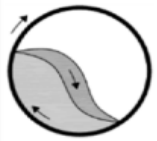
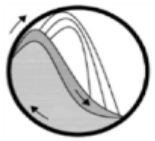
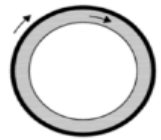
T2 Temp Measurement (i.e.Combustion Chamber Temp closer to flue gas discharge)

Temperature Probe Locations

Afterburner
Temp
Measurement

Scale-Up Analysis and Trial Settings

- Using a proprietary kinetic model, a residence time of **45 minutes** was predicted as being sufficient for Paper and Orange feed based on various properties (pellet shape, length, density, moisture content etc). This was reduced to **30 minutes** for Olive.
- The Froude number, $\mathbf{F_r = \omega^2 R/g}$, is defined as the ratio of centrifugal force to gravity, where ω, R and g are the tube rotational speed, tube radius and the gravitational acceleration, respectively. A tube rotational speed was selected to ensure that a Froude number in the **rolling** regime would occur (judged to be most appropriate for heat and mass transfer for the particular bed in question, as well as being more practical at commercial scale).
- A feed rate of **3 kg/h** was selected to mimic bed depths deemed applicable at larger scale for paper and orange pellets. **4 kg/h** was taken for Olive feed.

Basic Form	Slippping motion		Cascading motion			Cataracting motion	
Subtype	Sliding	Surging	Slumping	Rolling	Cascading	Cataracting	Centrifuging
Schematic							
Process	Slipping			Mixing		Crushing	Centrifuging
Froude Number	$0 \div 10^{-4}$		$10^{-5} \div 10^{-4}$	$10^{-4} \div 10^{-2}$	$10^{-3} \div 10^{-1}$	$0.1 \div 1$	> 1

PAPER Scale-Up Analysis and Trial Settings

Kiln Sizing - TNO - Paper

Kiln Model		**Trial Kiln**	**TR1200**	**TR2100**
Process Info				
Throughput (wet in)	kg/h	3	550	2000
Throughput (Dry & DeVol Out)	kg/h	1.18	217	790
Bulk Density In	kg/m^3	690	690	690
Moisture in	%	2%	2%	2%
Moisture out	%	0%	0%	0%
Target Temperature	degC	700	700	700
Volatiles in dry Feed	%	59.9%	59.9%	59.9%
Residence Time	minutes	45	45	45
Rotation Speed	rpm	3.7	1.4	1.05
Physical Dimensions / Fill:				
Diameter	m	0.1651	1.2	2.1
Length	m	2	7	12
Bed Depth In	%	13%	13%	10%
Bed Depth Out	%	6%	6%	5%
Solids Motion				
Froude Number		0.00126	0.00131	0.00129
Motion Form		Rolling	Rolling	Rolling

Basic Mass Balance

Paper

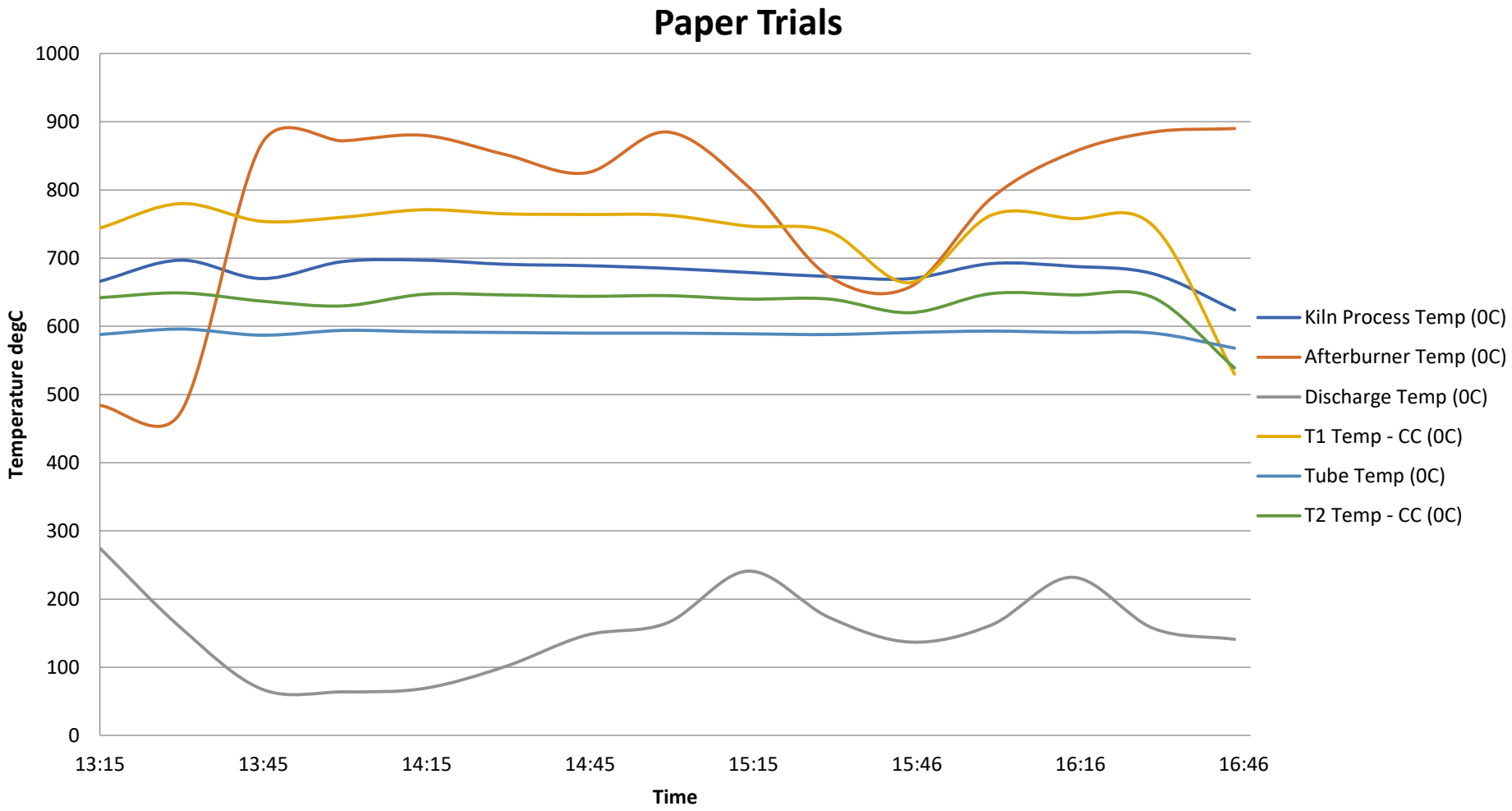
Volatiles	*59.9%*
Ash	*24.9%*
Moisture	*1.6%*

Total In	*9.00*	*kg*
Total Out	*4.11*	*kg*
Theoretical Best Conversion Out	*3.47*	*kg*

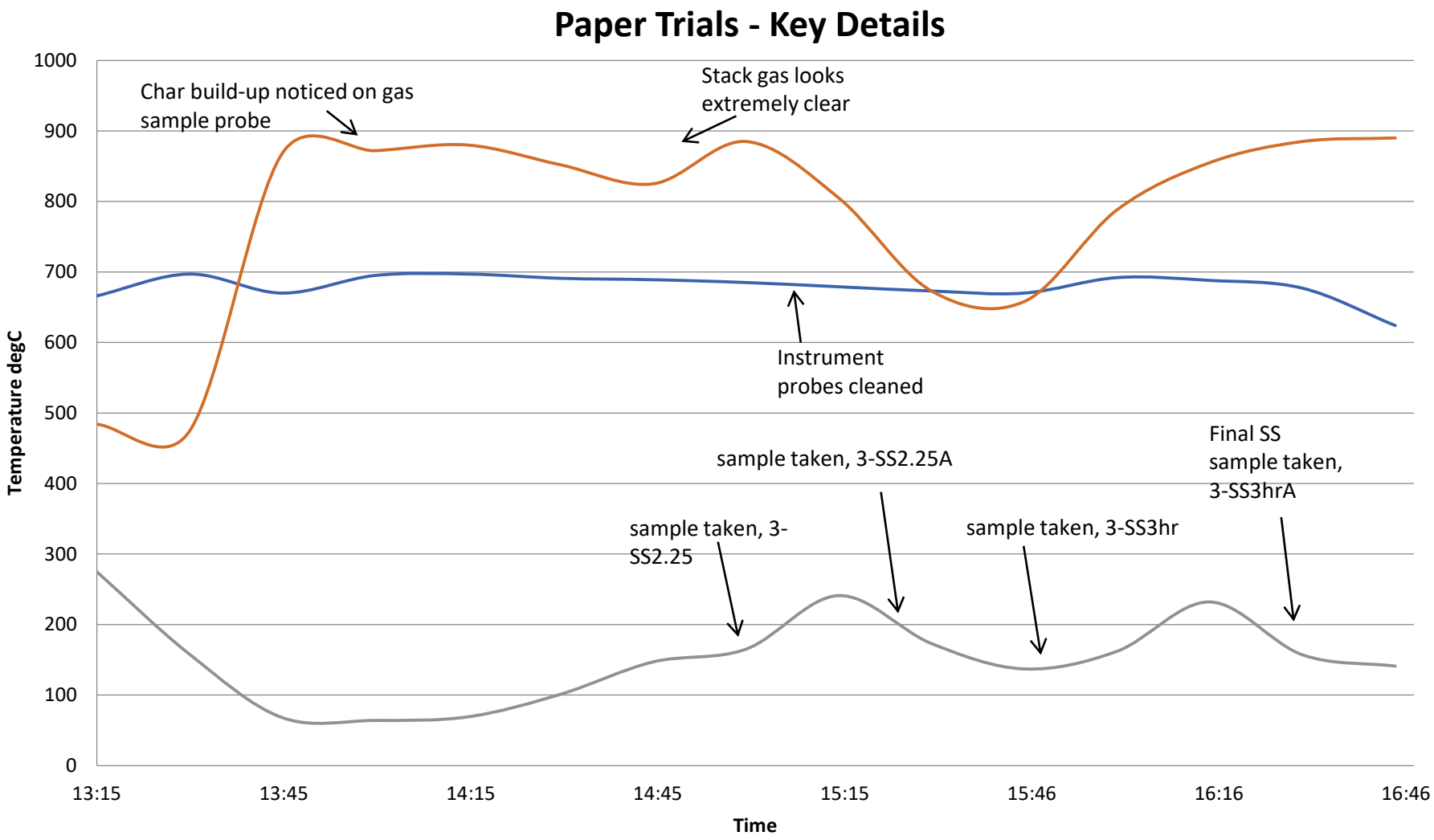
(i.e. only Ash and Fixed Carbon remaining)

Total Out	*46%*
Theoretical Best Conversion Out	*39%*

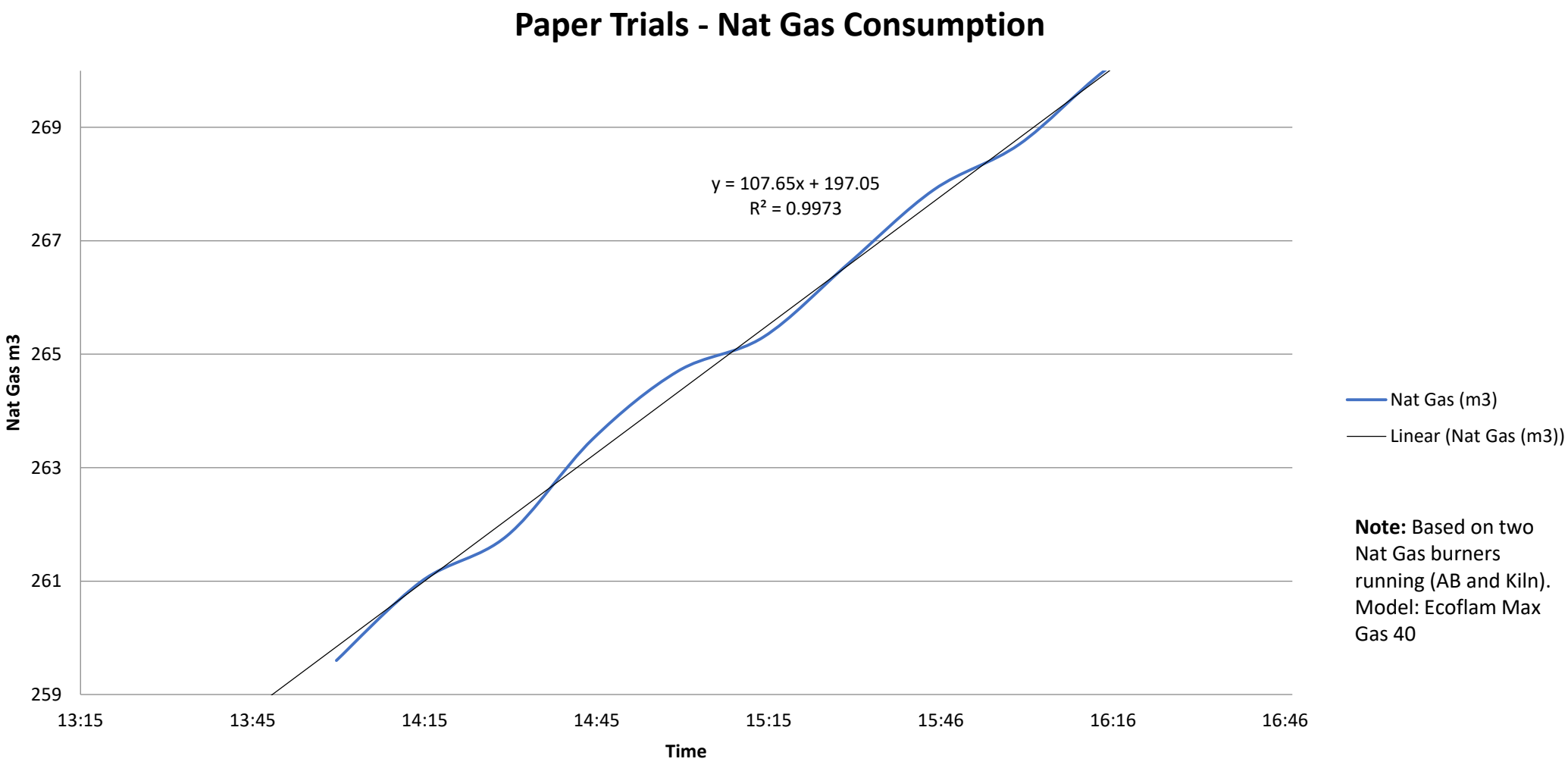
Trial Temperature Readings – 24/06/22



Trial Key Details – 24/06/22

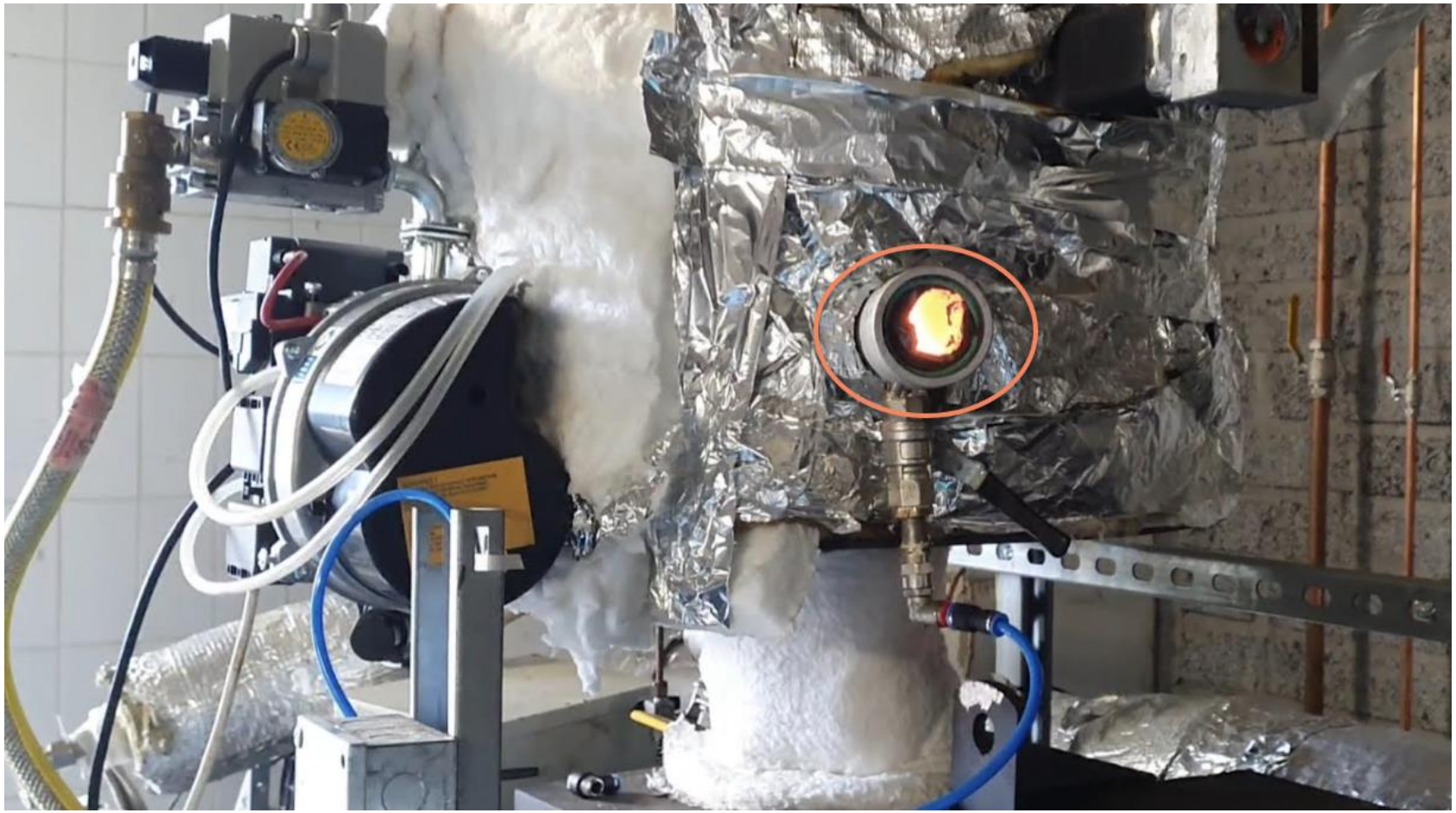


Trial Energy Consumption– Paper



Note: Based on two Nat Gas burners running (AB and Kiln). Model: Ecoflam Max Gas 40

Syngas Combustion in Afterburner



Syngas Combustion & Sampling

•Please double-click image to play movie

(Many Thanks to Marco and Johan for their excellent work)

Paper Pellets - Before and After

PAPER - Observations and Notes

•Performance was steady, with stable temperatures and good material flow.

•Cleaning of the gas sample probes was required to remove some char build-up.

•Based on the proximate analysis the max theoretical conversion achievable was 39% (i.e. 39% of the feed mass exits as char and ash). This would be the case with optimum operating conditions (temperature, residence time, bed depth etc). The calculated output was 46% of the input feed, representing a very good pellet conversion to char, closely approximating the theoretical value, thereby validating the calculated settings (i.e. temperature: 700degC, RT: 45mins, Regime: Rolling, Bed Depth: 13%). These parameters can be applied to equipment design and OPEX calculations at large scale.

• Charred pellet colour, shape and flowability all appeared as expected. The processed material appeared easy to handle.

OLIVE Scale-Up Analysis and Trial Settings

Kiln Sizing - TNO - Olive

Kiln Model		**Trial Kiln**	**TR1200**	**TR2100**
Process Info				
Throughput (wet in)	kg/h	4	750	2720
Throughput (Dry & DeVol Out)	kg/h	0.65	122	442
Bulk Density	kg/m^3	610	610	610
Moisture in	%	1%	1%	1%
Moisture out	%	0%	0%	0%
Target Temperature	degC	700	700	700
Volatiles in dry Feed	%	83.6%	83.6%	83.6%
Residence Time	Min	30	30	30
Rotation Speed	rpm	5.5	2	1.5
Physical Dimensions / Fill:				
Diameter	M	0.1651	1.2	2.1
Length	M	2	7	12
Bed Depth In	%	13%	13%	10%
Bed Depth Out	%	6%	6%	5%
Solids Motion				
Froude Number		0.00279	0.00268	0.00264
Motion Form		Rolling	Rolling	Rolling

Basic Mass Balance

Olive

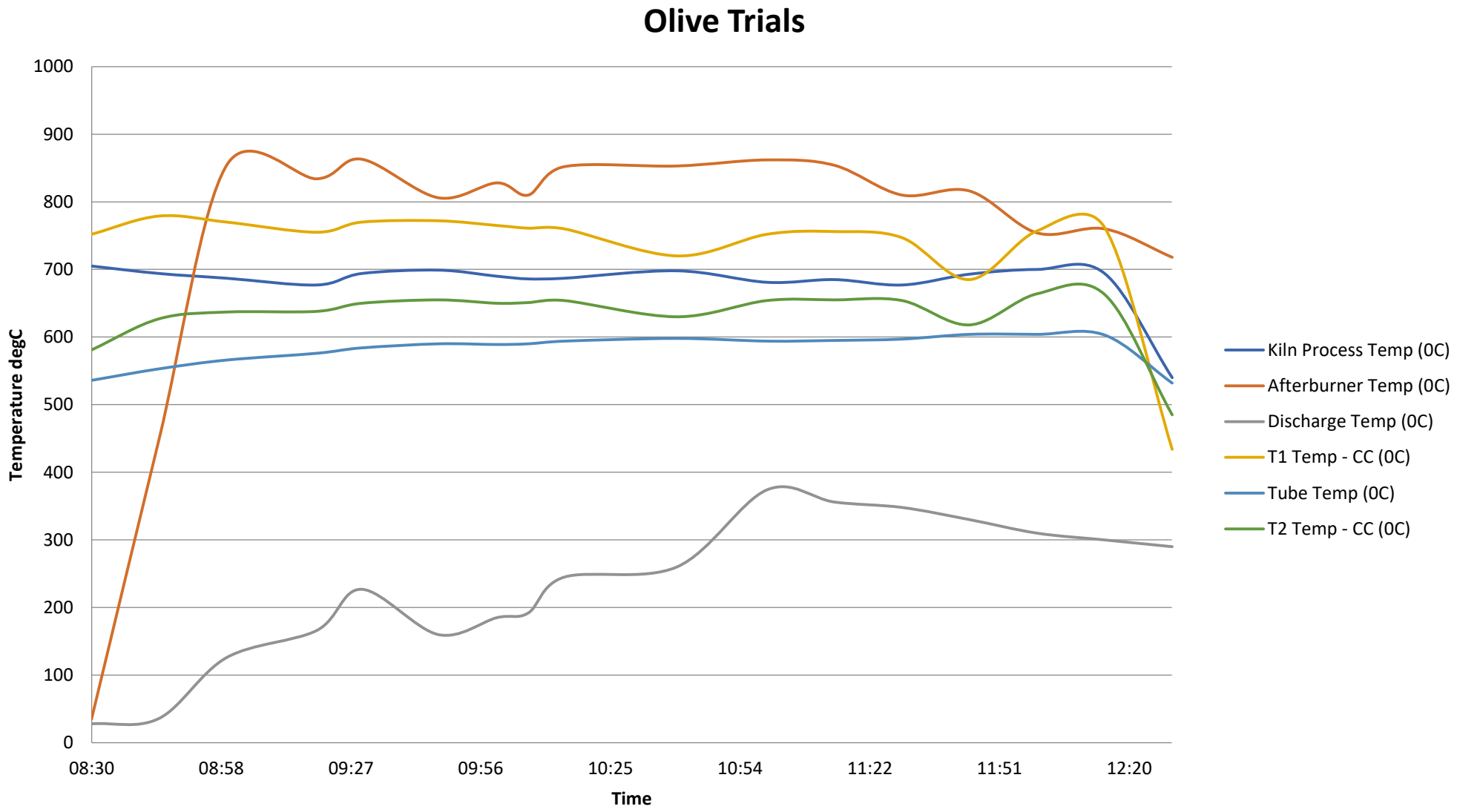
Volatiles	*83.6%*
Ash	*1.7%*
Moisture	*1.1%*

Total In	*16.00*	*kg*
Total Out	*2.90*	*kg*
Theoretical Best Conversion Out	*2.45*	*kg*

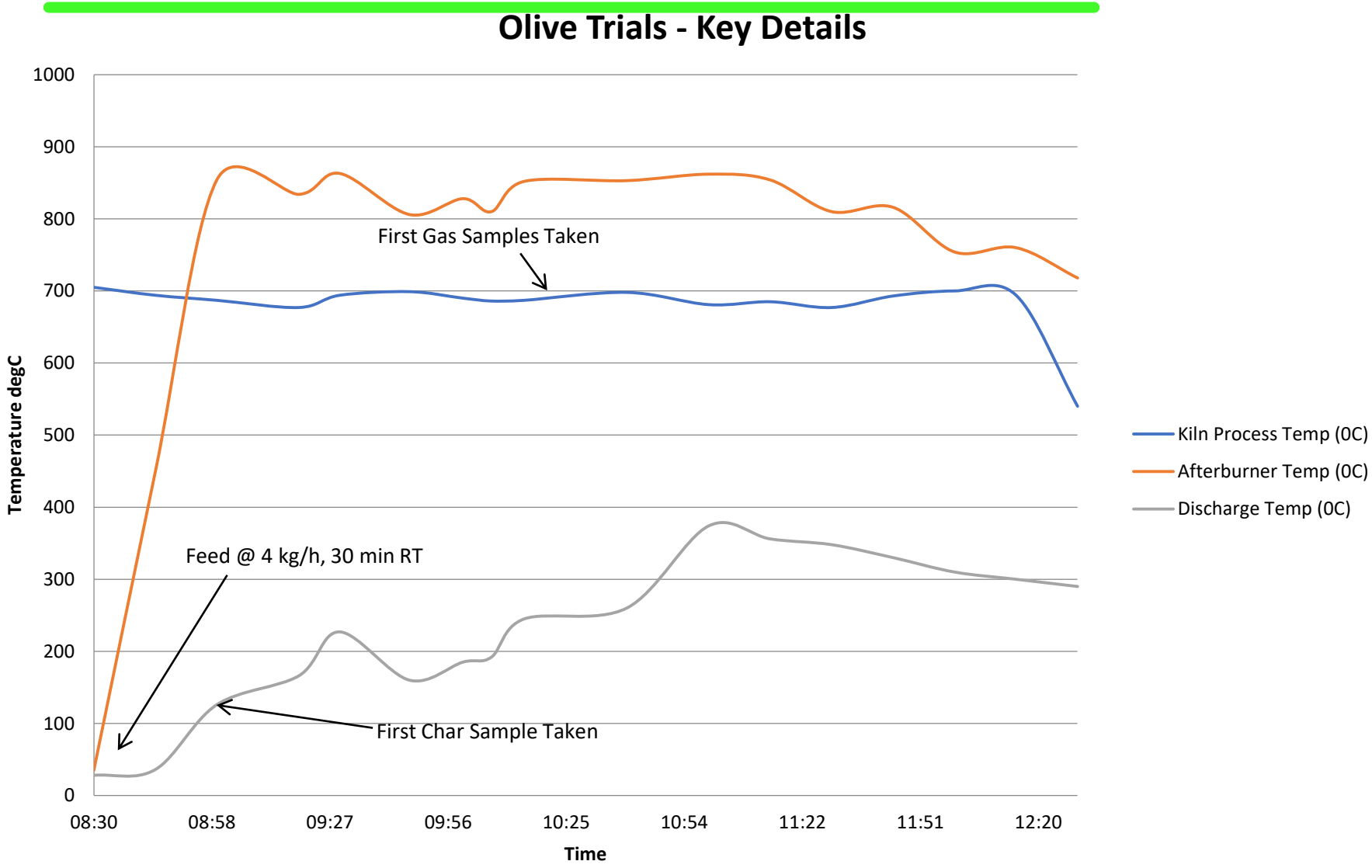
(i.e. only Ash and FC remaining)

Total Out	*18%*
Theoretical Best Conversion Out	*15%*

Trial Temperature Readings – 21/06/22



Trial Key Details – 21/06/22



Olive Pellets – ‘Very Powdery’

OLIVE - Observations and Notes

•Performance was steady, with stable temperatures and reasonable material flow after some olive powder compaction issues were overcome in the feed-screw. The material was not pellet-like, and more closely resembled lumps and dust. It may benefit from blending with paper sludge, orange or similar to form a more robust pellet.

•A significant quantity of syngas was generated, possibly overloading the afterburner. This material is well suited to syngas generation, having the benefit of a very high volatile fraction. Gas handling equipment will present the bottleneck for scale-up sizing (likely requiring de-rating of kiln throughput to accommodate).

•Based on the proximate analysis the max theoretical conversion achievable was 15% (i.e. 15% of the feed mass exits as char and ash). This would be the case with optimum operating conditions. The calculated output was 18% of the input feed, representing excellent feed conversion to char, closely approximating the theoretical value, thereby validating the calculated settings (i.e. temperature: 700degC, RT: 30mins, Regime: Rolling, Bed Depth: 13%). These parameters can be applied to equipment design and OPEX calculations at large scale.

• Charred product colour, shape and flowability all appeared as expected. The processed material appeared easy to handle.

ORANGE - Scale-Up Analysis and Trial Settings

Kiln Sizing - TNO - Orange

Kiln Model		**Trial Kiln**	**TR1200**	**TR2100**
Process Info				
Throughput (wet in)	kg/h	3	550	2000
Throughput (Dry & DeVol Out)	kg/h	0.90	165	601
Bulk Density	kg/m^3	682	682	682
Moisture in	%	2%	2%	2%
Moisture out	%	0%	0%	0%
Target Temperature	degC	700	700	700
Volatiles in dry Feed	%	69.5%	69.5%	69.5%
Residence Time	Min	45	45	45
Rotation Speed	rpm	3.7	1.4	1.05
Physical Dimensions / Fill:				
Diameter	M	0.1651	1.2	2.1
Length	M	2	7	12
Bed Depth In	%	13%	13%	10%
Bed Depth Out	%	6%	6%	5%
Solids Motion				
Froude Number		0.00126	0.00131	0.00129
Motion Form		Rolling	Rolling	Rolling

Basic Mass Balance

Orange

Volatiles	*69.5%*
Ash	*2.0%*
Moisture	*1.5%*

Total In	*9.00*	*kg*
Total Out	*2.53*	*kg*
Theoretical Best Conversion Out	*2.61*	*kg*

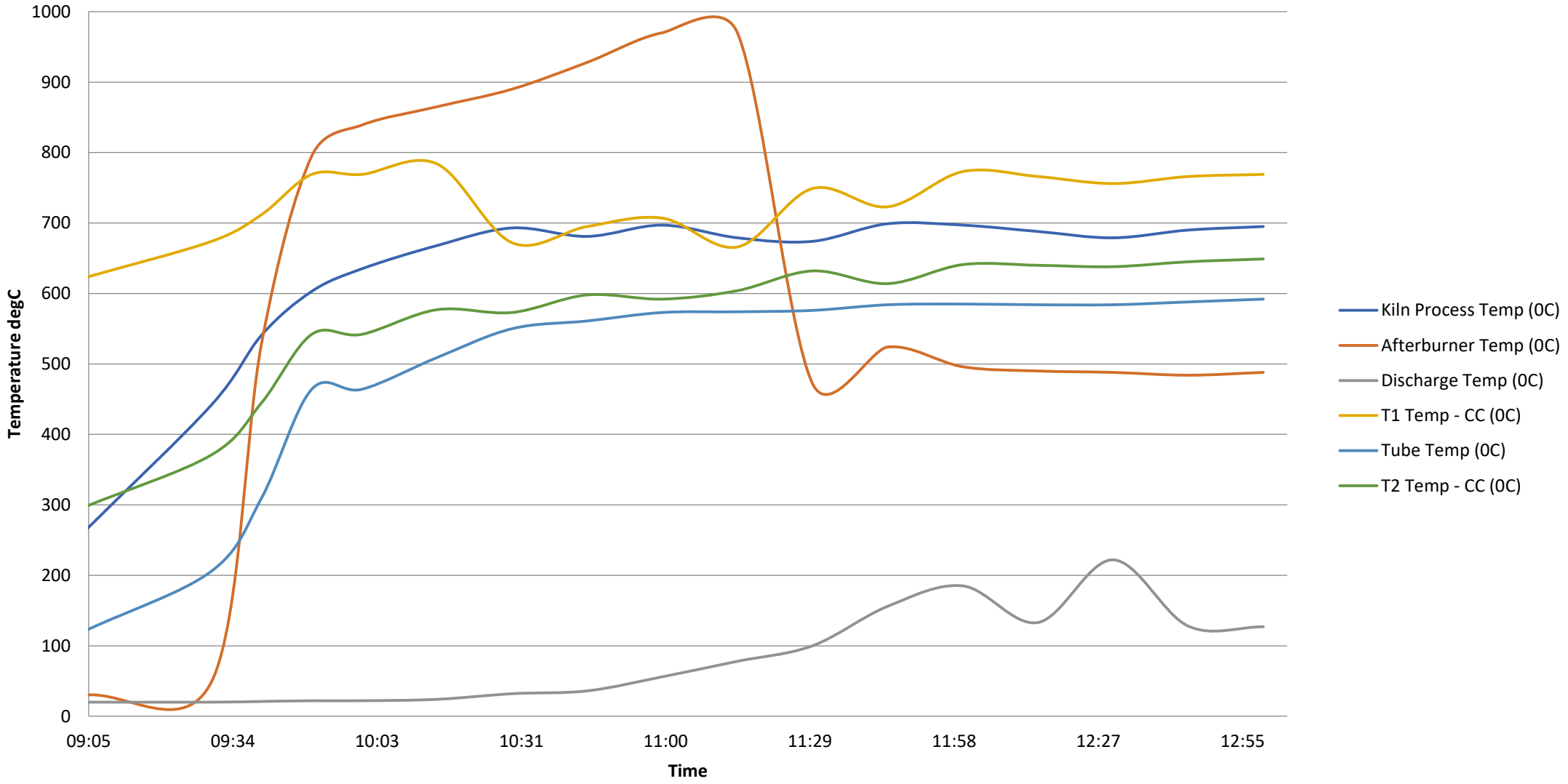
(i.e. only Ash and FC remaining)

Total Out	*28%*
Theoretical Best Conversion Out	*29%*

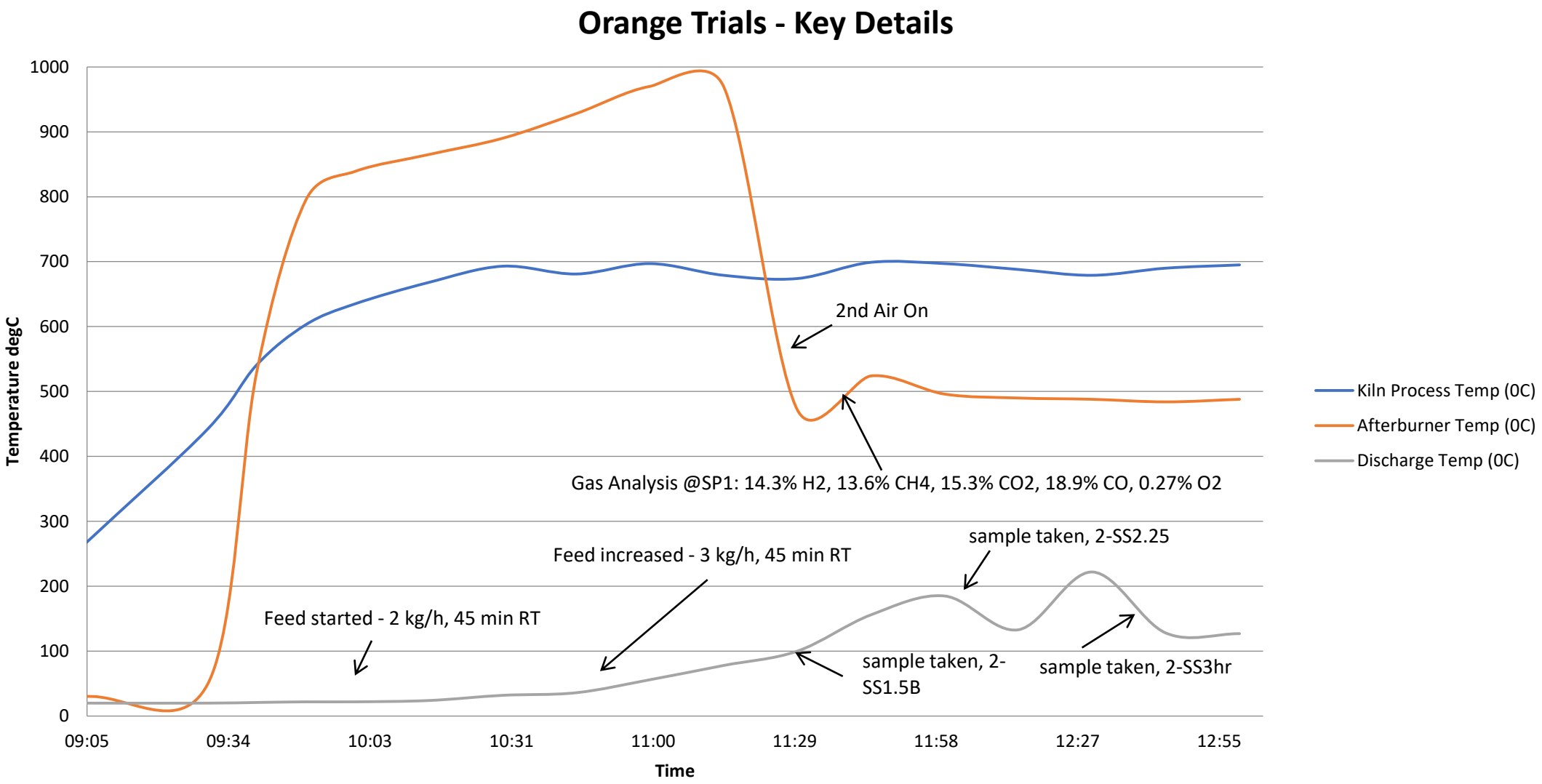
(i.e. ~100% conversion accounting for dust losses, scales calibration, natural variation in composition etc)

Trial Temperature Readings – 24/06/22

Orange Trials

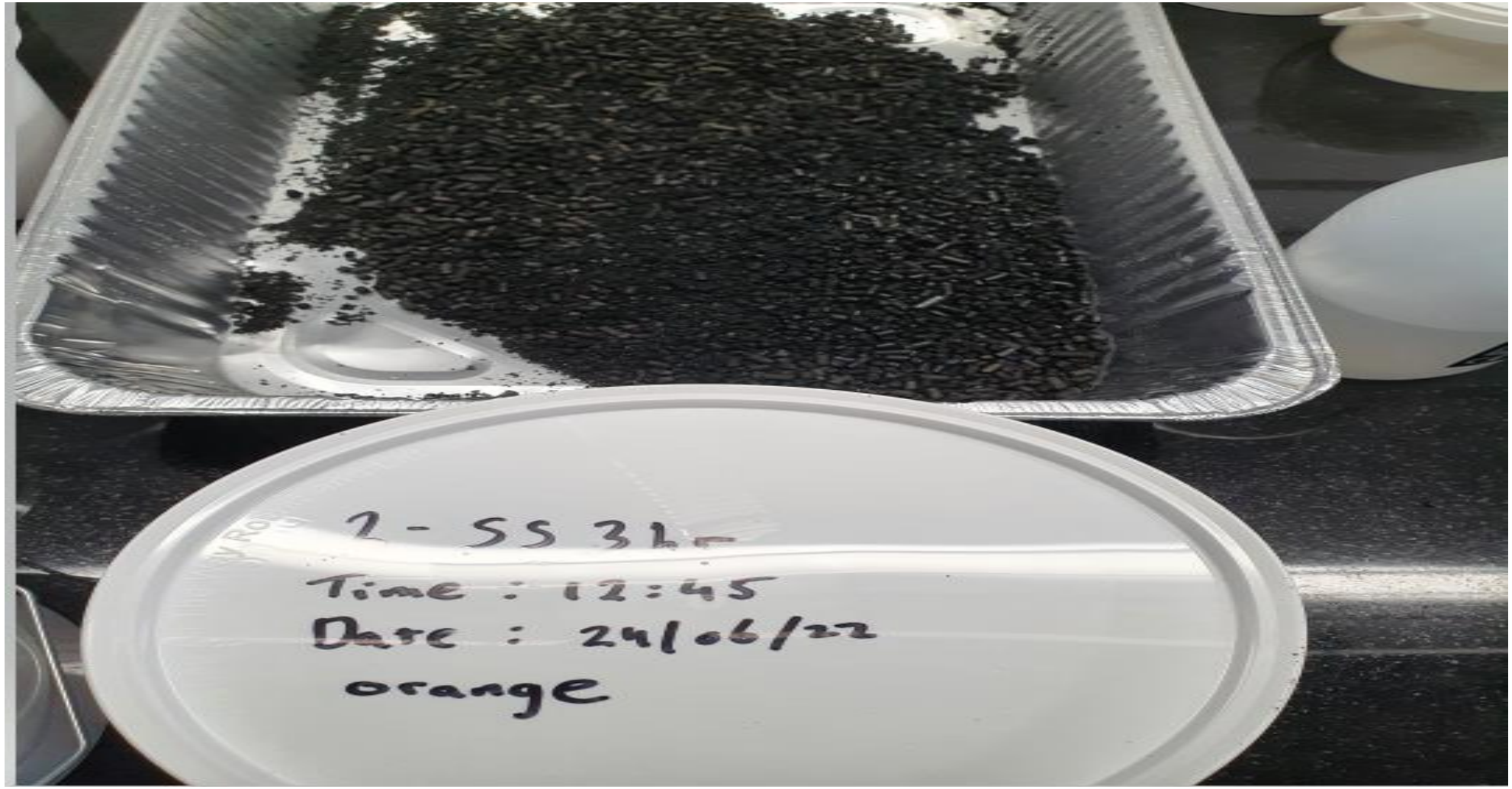


Trial Key Details – 24/06/22



Orange Pellets – ‘Very Robust’

Orange Pellets – Converted to Char



Observations and Notes

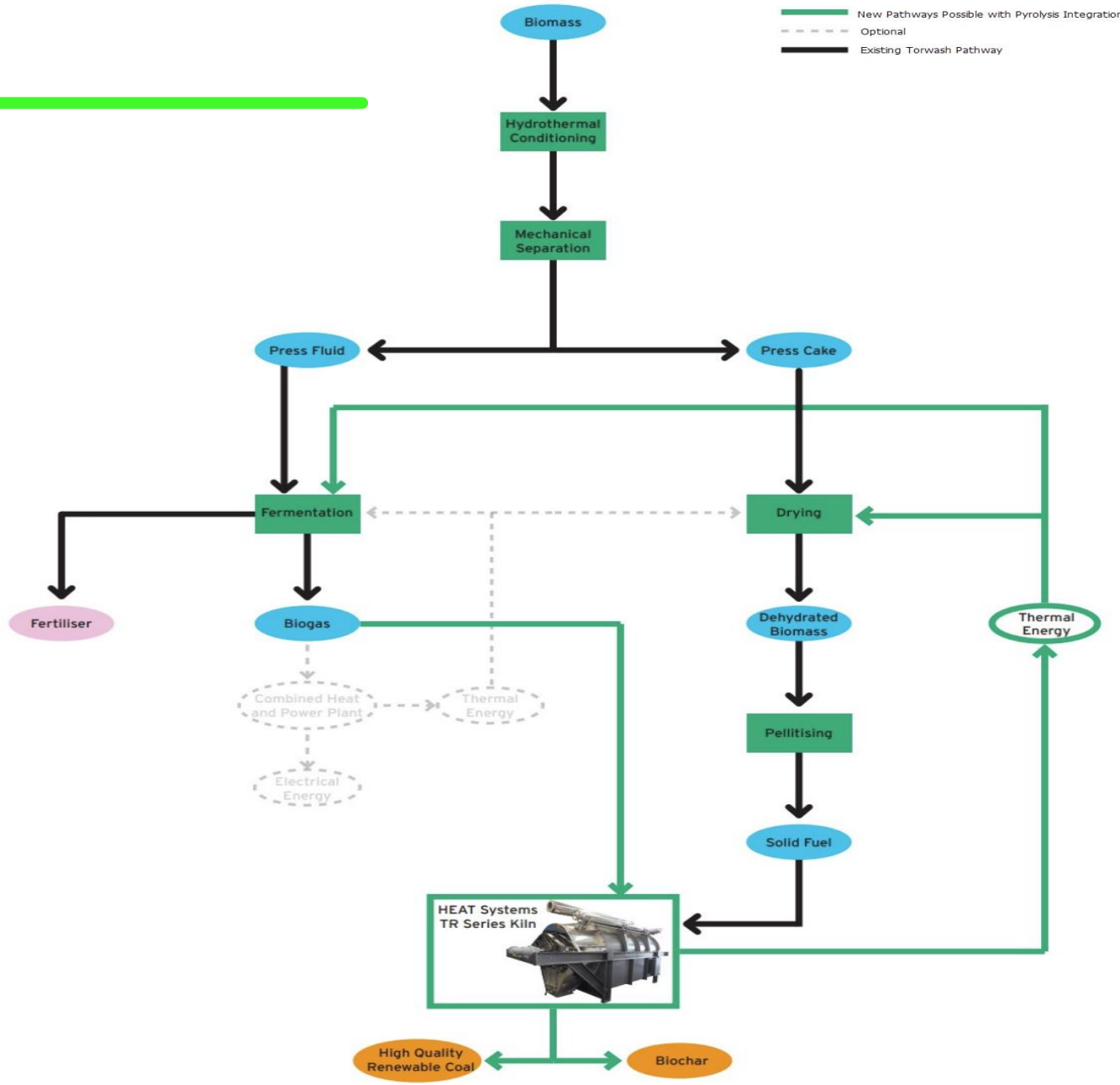
•Performance was steady, with stable temperatures and good material flow.

•Based on the proximate analysis the max theoretical conversion achievable was 29% (i.e. 29% of the feed mass exits as char and ash). This would be the case with optimum operating conditions (temperature, residence time, bed depth etc). The calculated output was 28% of the input feed (accounting for minor losses, scales calibration error etc) representing a very satisfactory pellet conversion to char, thereby validating the calculated settings (i.e. temperature: 700degC, RT: 45mins, Regime: Rolling, Bed Depth: 13%). These parameters can be applied to equipment design and CAPEX / OPEX calculations at large scale.

• Charred pellet colour, shape and flowability all appeared as expected. The processed material appeared easy to handle.

Synergies

The schematic shows the potential synergy and integration between F-Cubed processes, Anaerobic Digestion and Pyrolysis. Combining all systems amplifies benefits in terms of value-added outputs.



Scale-up

Scale-up

THANK YOU

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