CONFIDENTIAL

ETN H2 - IGCC

SP1.3 “Combustion”

Cardiff University Progress Report July 2013

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Executive Summary

This report summarises the H2-IGCC SP1.3 combustion activities at the Cardiff University Gas Turbine Research Centre (GTRC) from 1st Jan 2013 up to 5th June 2013. Table 1 shows the conditions tested, note also that burner 'mapping' took place with Configurations 4.1 and 4.2, which involved testing emissions and stability of the design at a number of simulated engine conditions.

Table 1: Experimental results

	Config 3.2	Config 3.3	Config 4.1	Config 4.1	Config 4.1	Config 4.2	Config 4.2
Diagonal Swirler	Multinozzle (S0839)	Multinozzle (S0840)	Multinozzle (S0839)	Multinozzle (S0839)	Multinozzle (S0839)	Multinozzle (S0839)	Multinozzle (S0839)
Nozzle / CBO Configuration	STD CBO	STD CBO	STD CBO	STD CBO	STD CBO	RDA 25 CBO	RDA 25 CBO
Fuel Entry Location	**Syngas Entry Through Swirl Vanes. 1mm holes**	**Syngas Entry Through Swirl Vanes. 2.2mm holes**	**Syngas Entry Through Swirl Vanes. 1mm holes**	**Syngas Entry Through Swirl Vanes. 1mm holes**	**Syngas Entry Through Swirl Vanes. 1mm holes**	**Syngas Entry Through Swirl Vanes. 1mm holes**	**Syngas Entry Through Swirl Vanes. 1mm holes**
Main Burner Fuel	**Syngas 2**	**Syngas 2**	**Syngas 2**	**Syngas 2**	**Syngas 2**	**Syngas 2**	**Syngas 2**
Pilot	**None**	**None**	**None**	**None**	**None**	**None**	**None**
Power kW	500	500	500	750	1000	1000	1500
Combustor Exhaust Temp C	1063	1042	Tested under engine mapping conditions, please see individual results for the pressures and power setting evaluated.				
Burner Tip Temp C	380	376					
Exhaust Dynamics (mb pk-pk)	6	6					
NOx (wet 15%O2 ppm) / NOx (Dry 15%O2 ppm)	3.4/..	9/..					
CO (dry 15% O2 ppm)	<4	<4					
THC (wet 15% O2 ppm) / THC (Dry 15%O2 ppm)	<4/..	<4..					
O2 dry %	14.84	14.75					
CO2 dry %	0	0					
Comments	Stable	Flame appears less wel mixed compared to 3.2	Stable	Stable	Flashback at Base Load	Stable. Higher Nox than Configuratio n 4.1	Flashback at Baseload

Configurations 3.2 and 3.3 were tested as per the methods used in the previous progress reports; they were stable at the 500kWth condition, with and without a methane pilot. There were no obvious signs of partial or full flashback during the extended running period, with the burner tip temperature remaining constant. There were also no signs that the flame would blow off, although with configuration 3.3 the flame appeared visually less well mixed. The raw exhaust dynamic pressure measurements of 6mbar peak to peak, compare favourably with the standard natural gas burner measurements, performed earlier in the H2IGCC GTRC campaign. The NOx emissions were steady at 3.4 and 9 ppm, for configuration 3.2 and 3.3 respectively which is encouraging as the target level for Ansaldo is <15ppm. These levels will need to be revised to take into account the water vapour in the exhaust and adjusted for 15%

O_2 in the exhaust. Ansaldo decided that configuration 3.2 was the most favourable for further testing at engine operating conditions.

Test campaign 4 (i.e. configurations designated as 4.1 and 4.2) involved burner mapping at simulated engine conditions. This showed encouraging results for flame stability, dynamics (acoustic oscillation) and NOx. The testing showed that NOx abatement technology will likely be required at base load and 70% base load. Elevated pressure experiments performed with configuration 3.2, (reallocated as 4.1 to indicate the next phase in the test programme). Gave acceptable performance at the 1.5 bara condition, but flashback became a problem at the baseload condition at 2.0 bara. To alleviate this, the CBO area was reduced by using the RDA 25 CBO and designating this configuration as 4.2 (or 3.2a). This configuration enabled the 2.0 bara baseload condition to be met although NOx levels were higher with this configuration. Flashback became a problem again at the 3.0 bara baseload condition. At this point it was clear that by maintaining the $m\sqrt{T}/P$ relationship the chemical kinetics of the fuel/air mixture must be changing with pressure. It was concluded that the fuel air mixture became more reactive enabling the flame front to recede towards the burner tip either through the boundary layer or shear layer.

Experimental Setup

Since the 31st December 2012 report further improvements to the gas delivery system have been made which enable longer testing times with premixed syngas. Results presented in this report relate to Syngas burner configurations 3.2, 3.3, 4.1 and 4.2 which are summarised in Figure 1.

(a) (b) (c)

Figure 1: Syngas burner configurations (a) is 3.2 & 4.1, (b) is 3.3 (c) is 3.2a & 4.2.

Syngas is delivered through what would normally be used as the methane premix main holes, located in the swirl vanes which have been highlighted by red circles in Figure 1. In burner Configuration 3.2 there are five 1.0mm diameter holes in each side of the swirl vane and there are a total of 18 swirl vanes. In burner Configuration 3.3 there are five 2.2mm diameter holes in each side of the swirl vane and there are a total of 18 swirl vanes. The location of the syngas injection holes does provide a challenge to the operation of the burner for dual fuel purposes.

19th April 2013 - Syngas Burner Configuration 3.2. Syngas 2

The facility log data can be seen in Figure 2, which shows the test of Configuration 3.2 held at a stable operating condition of 500kWth between 14:40 and 15:00. Gas analysis data can be seen in Figure 3.

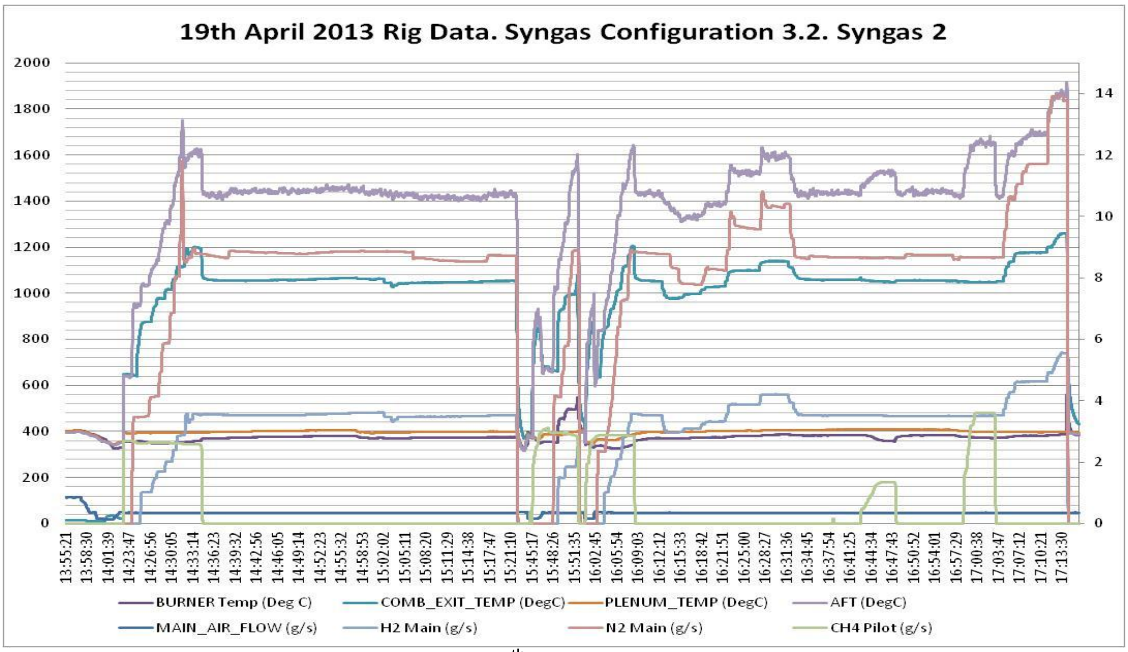


Figure 2: 19th April rig conditions

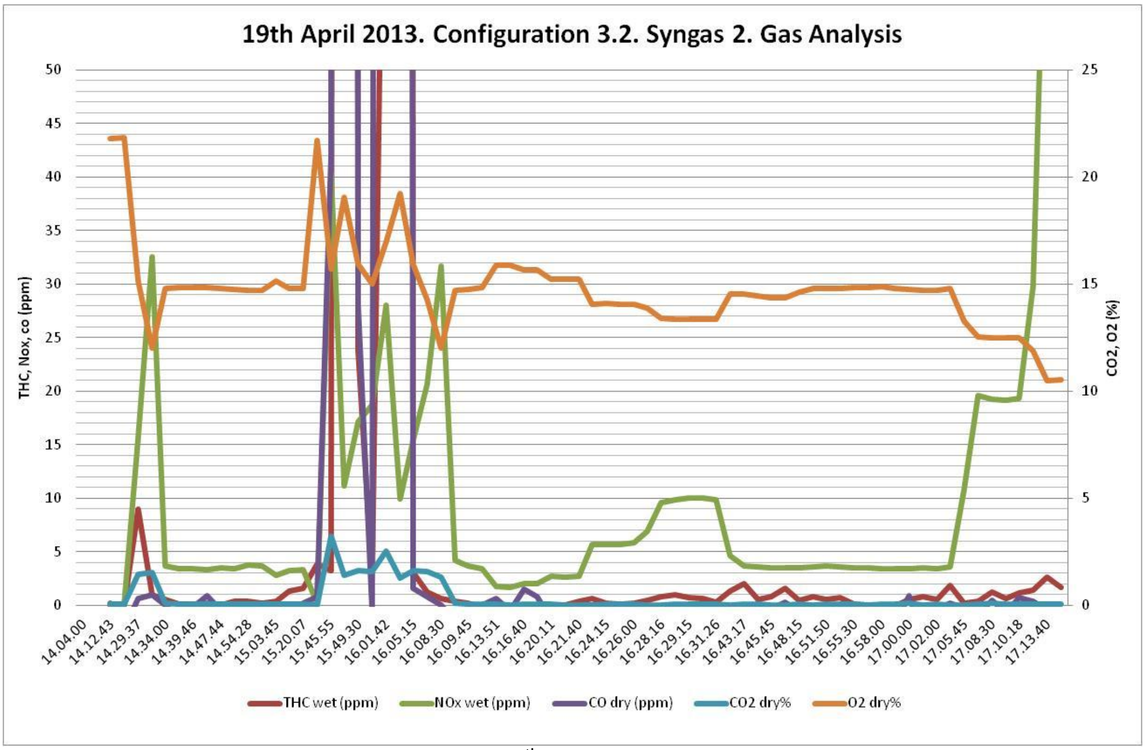


Figure 3: 19th April gas analysis

During this period with the premix syngas main only (No Pilot), NOx levels of 3.4ppm were measured which were the lowest from all the burner configurations tested to date. The data will need to be processed to take into account of the water vapour in the exhaust and adjusted for 15% O_2, but it is an encouraging result. A photograph of the syngas flame at this condition can be seen in Figure 4. It can be seen that the flame is visible with the use of a HD camera probably due to increased sensitivity in the ultra violet spectrum. The flame is very homogenous which is an indication of good fuel/air mixing. It can be seen that the flame attaches to the CBO although no increasing temperature of the CBO was observed.

Figure 4: 19th April. Configuration 3.2. 500 kWth axial syngas flame

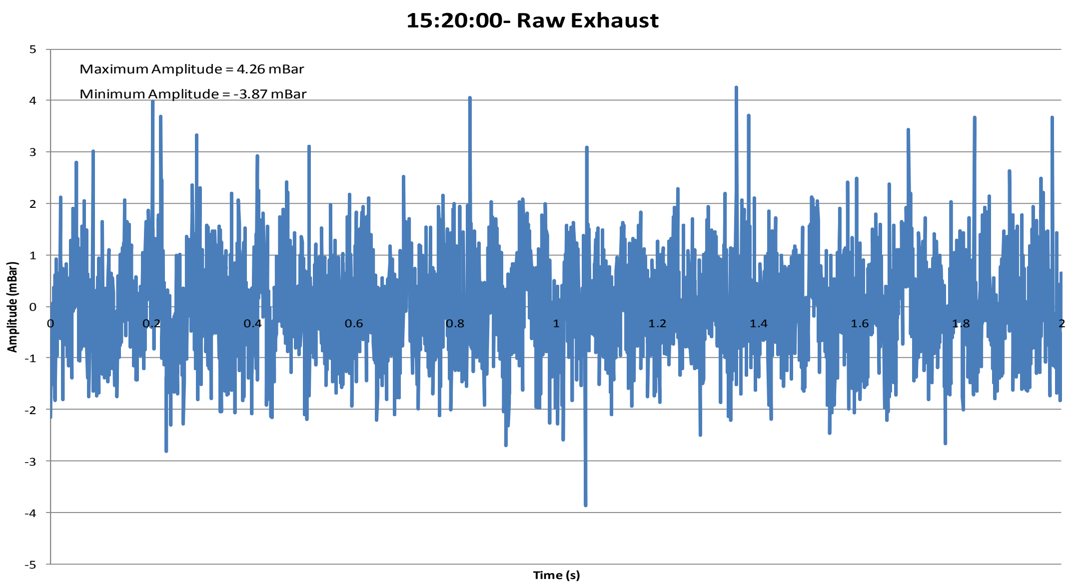


Figure 5: 19th April. Configuration 3.2. Raw exhaust transducer data without pilot

Typical raw exhaust pressure transducer measurements taken over a 2 second burst during this period can be seen in Figure 5 and show pressure levels at approximately 6mb peak to peak which is comparable to the standard natural gas burner tests undertaken at GTRC. The

FFT spectra for the period captured in Figure 5 for the 3 pressure transducers (inlet, combustor and exhaust) can be seen in Figure 6.

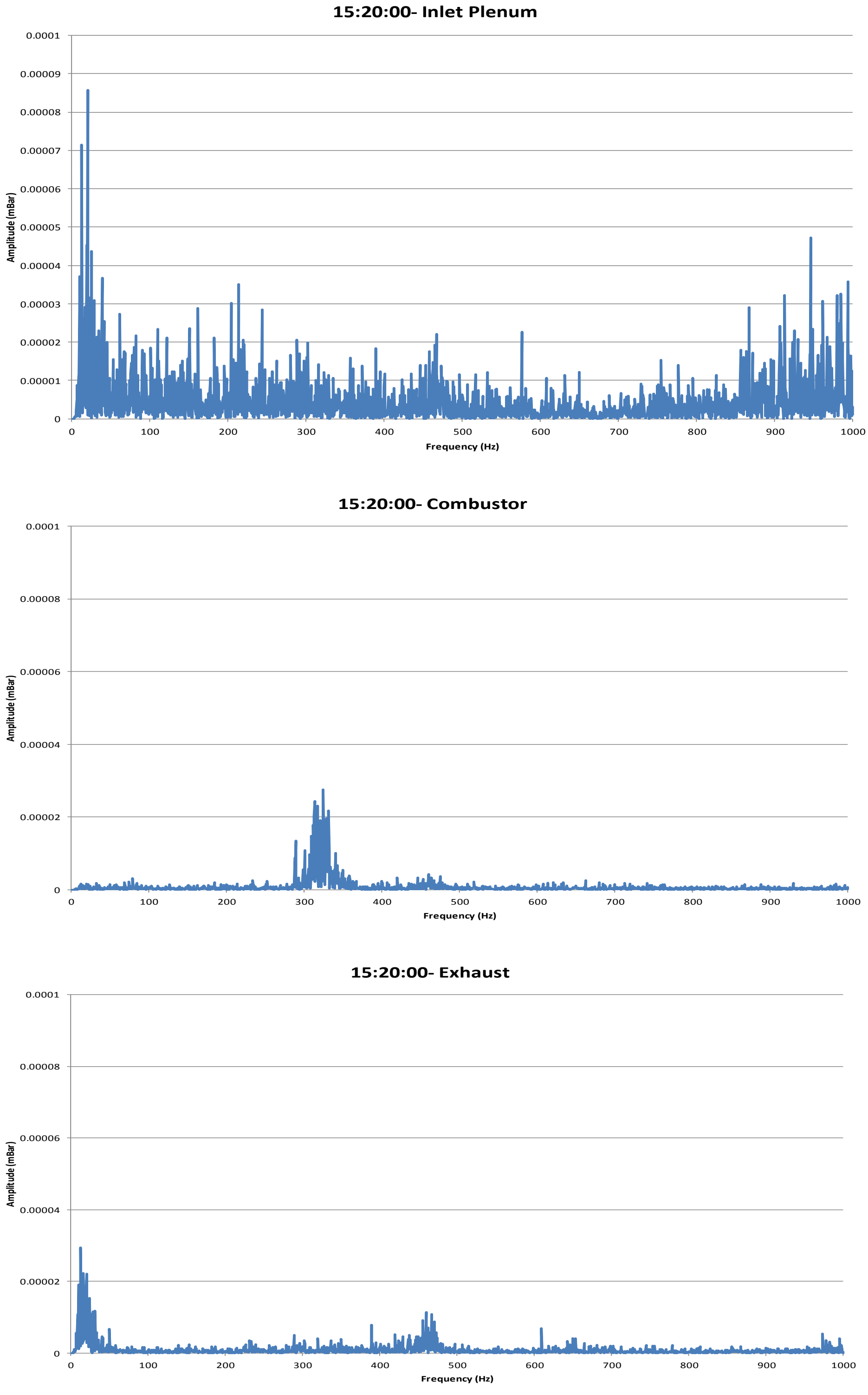
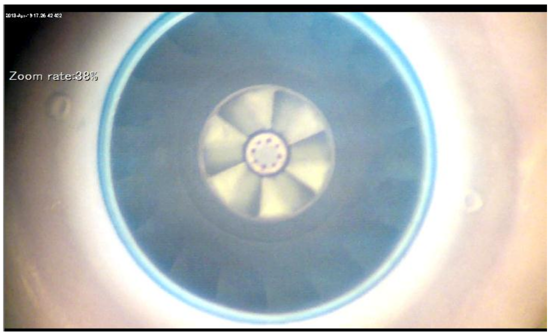


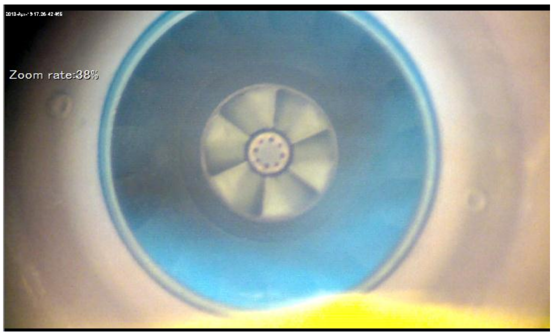
Figure 6: 19th April. Configuration 3.2. FFT spectra without pilot (inlet, combustor, exhaust).

During a period of stable burner operation between 16:42 and 17:02, the effect of argon and helium injection through the natural gas pilot line was observed. The hypothesis that noble gases would fluoresce making the flame more visible was tested. Firstly, helium was added up to a concentration of 9% by mass (14%vol). Secondly, argon was added to a concentration of 22% by mass (4%vol). No significant changes were observed to the flame shape or fluorescence. Furthermore, no significant change was observed with the NOx levels. Between 17:04 and 17:14 the equivalence ratio was increased with the addition of more syngas to investigate the effect of increasing Adiabatic Flame Temperature (AFT) on burner operation. It can be seen from Figure 3 that NOx levels start to increase significantly with increasing AFT. Flashback was observed (See Figure 7) at a local equivalence ratio of 0.54 and AFT of 1880°C. The flashback appeared to start at the bottom of the CBO which may suggest some asymmetric aerodynamic effects caused by the fuel delivery pipework upstream on the diagonal swirler resulting in a richer zone at the bottom of the CBO.

Time = 0

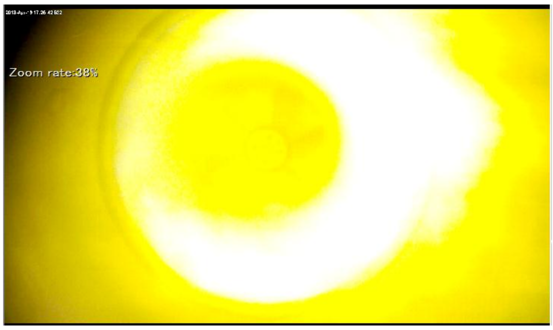
Time = 40ms





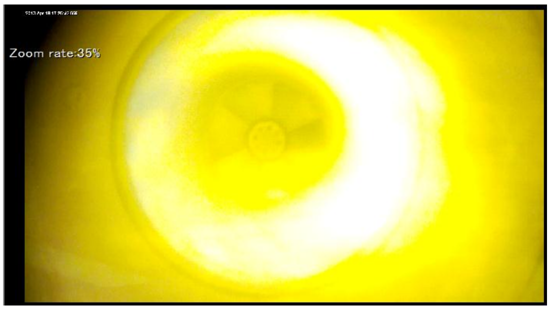
Time = 80ms

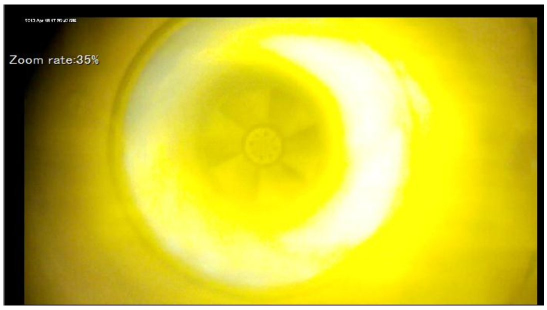
Time = 120ms



Time = 160ms

Time = 200ms





Time = 240ms

Time = 280ms

Figure 7: 19th April. Burner Configuration 3.2 undergoing syngas premix flashback

The raw exhaust pressure transducer measurements taken during the period leading up to the flashback event can be seen in Figure 8 and shows pressure levels at approximately 6mb peak to peak. Further analysis of these raw signals shows the existence of dominant frequencies in the signal in this case.

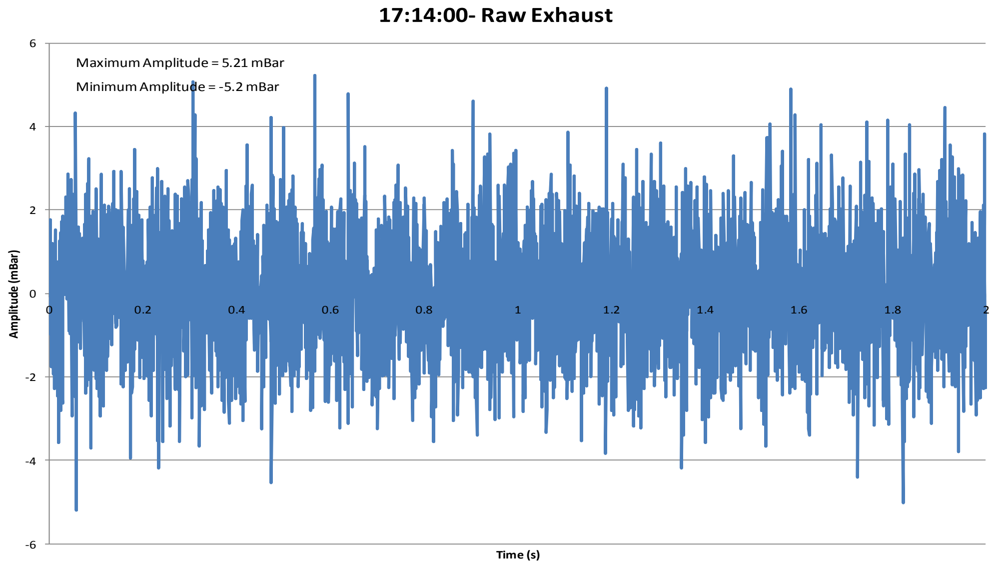


Figure 8: 19th April. Configuration 3.2 raw exhaust transducer data before flashback.

It was observed that prior to flashback all three pressure transducers seem to synchronise, i.e. the apparent dominant frequency of 290Hz existed at all 3 locations, as can be seen in Figures 9,10 and 11.

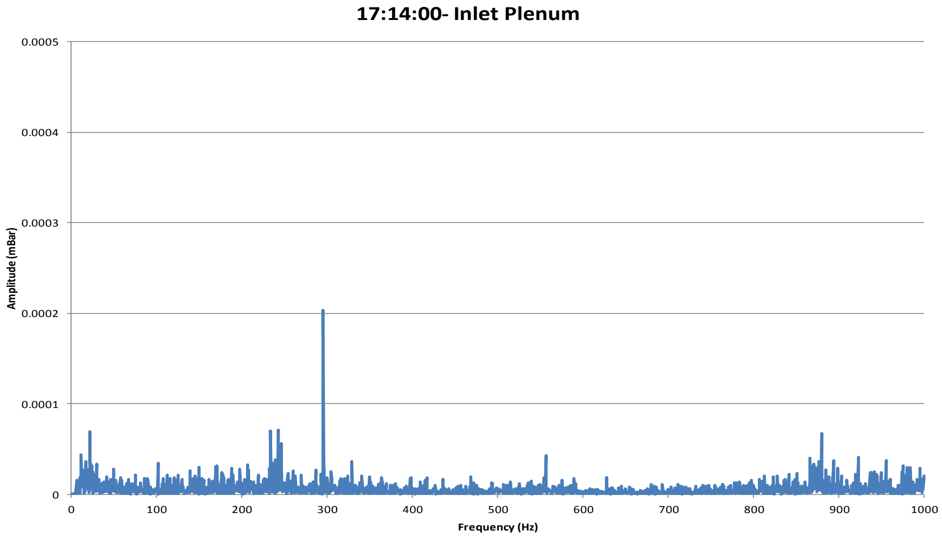


Figure 9: 19th April. Configuration 3.2. Inlet plenum FFT spectra

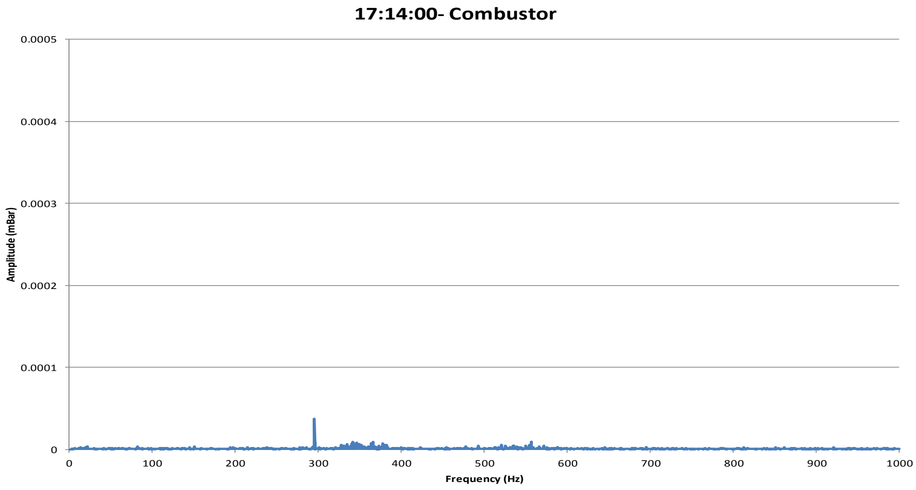


Figure 10: 19th April. Configuration 3.2. Combustor FFT spectra

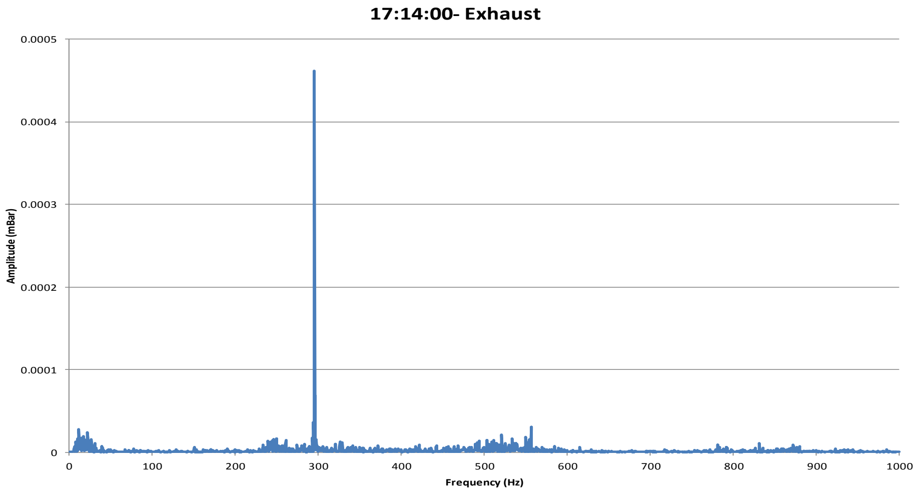


Figure 11: 19th April. Configuration 3.2. Exhaust FFT spectra

When there is synchronisation between the pressure transducers the amplitude of the narrow band is sufficient that it is the dominant frequency. As the flame approaches its flashback limit the amplitude in the plenum increases, and past a certain point so does the exhaust. This occurs at the same frequency whilst the flame recedes toward/into the CBO. The effect in the exhaust is greater than in the plenum, in terms of amplitude change; and when approaching flashback the amplitude in the exhaust exceeds that of the inlet. When the exhaust amplitude reached 0.8 mbar flashback occurred which is illustrated in Figure 12.

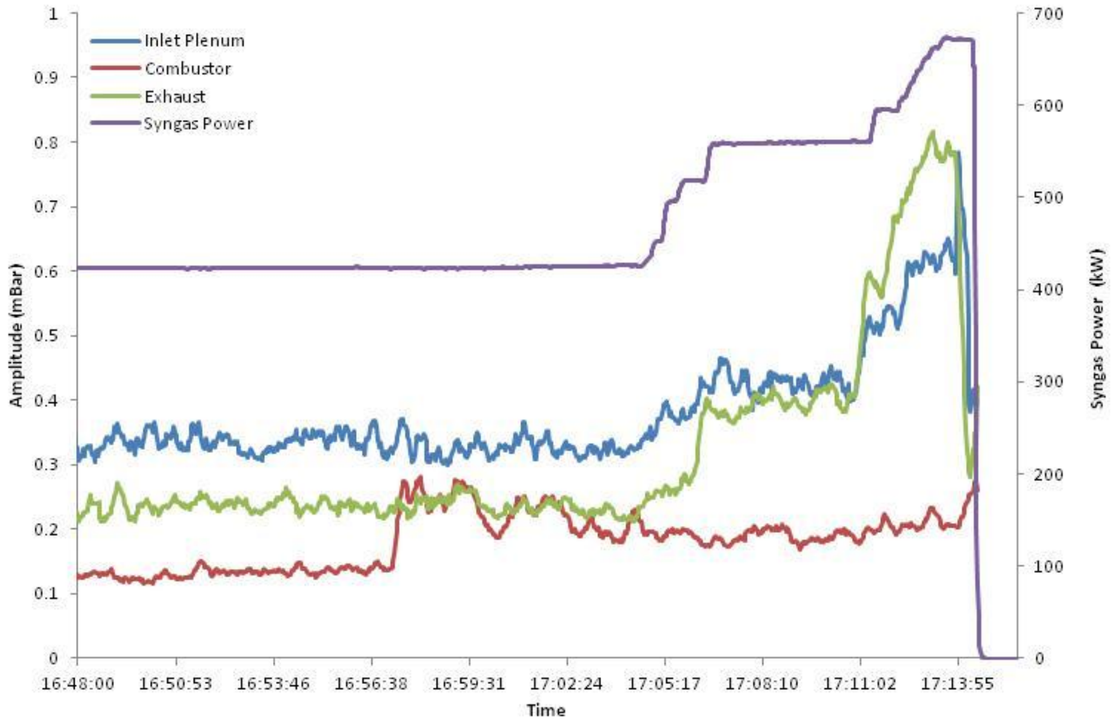


Figure 12: 19th April. Configuration 3.2. FFT peak amplitudes; flashback event occurring at 17:14:00.

It is therefore postulated that in the 3 locations where these dynamic pressure measurements were taken, synchronisation of the oscillations and/or the amplitude of the dominant frequency could be used as indicators to the onset of flashback.

23rd April 2013 - Syngas Burner Configuration 3.3. Syngas 2

The facility conditions can be seen in Figure 13. Between 16:42 and 17:32 the burner was operated with the syngas premixed main with a thermal input of 500kW. The gas analysis data can be seen in Figure 14.

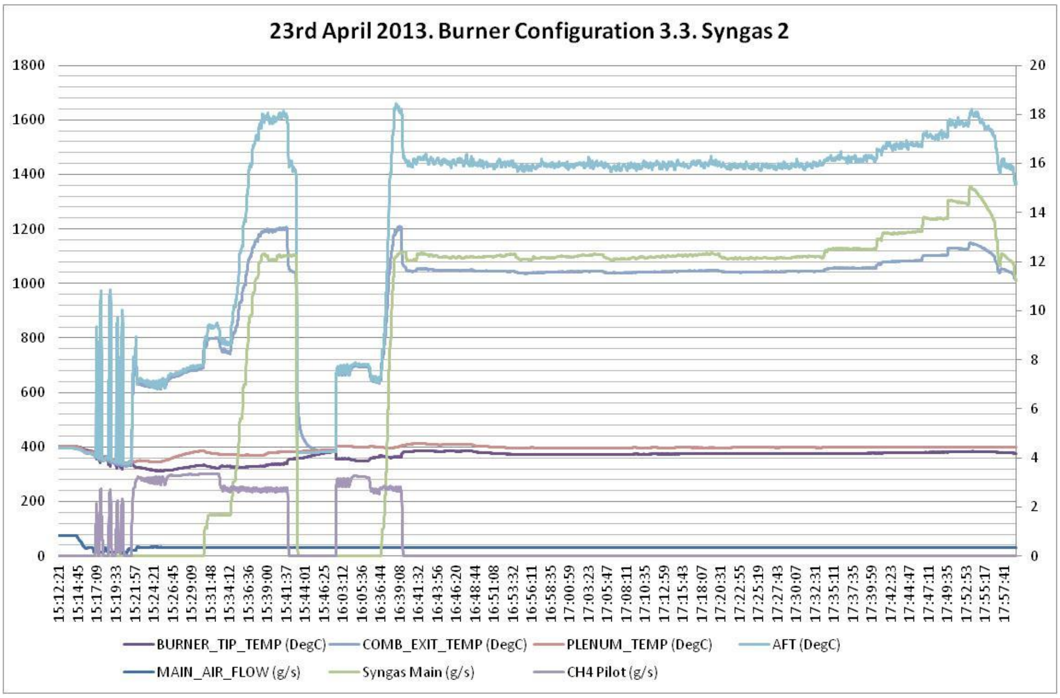


Figure 13: 23rd April rig conditions

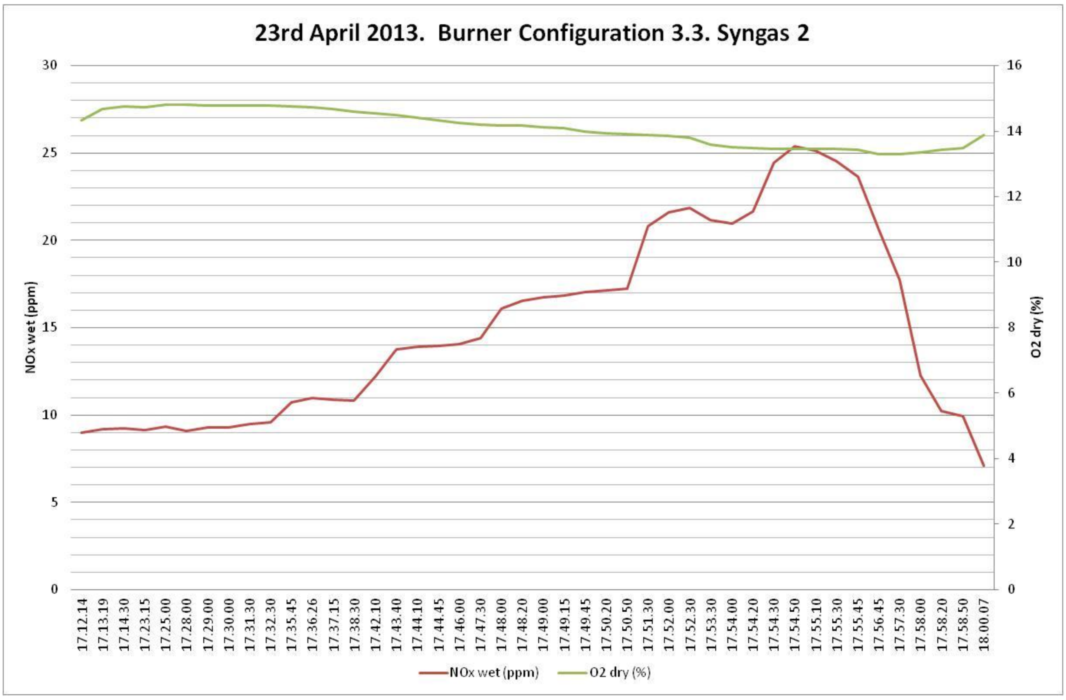


Figure 14: 23rd April gas analysis

During this period with the premix syngas main only (No Pilot), NOx levels of 9ppm were measured, which was higher than Configuration 3.2 for this condition, but lower than Configuration 3.1. The data will need to be processed to take into account the water vapour in the exhaust and adjusted for 15% O_2.

Photographs of the syngas flame on condition can be seen in Figures 15 and 16. The flame was not as homogeneous in comparison with the observations made for burner Configuration 3.2 and more flame flicker was observed during the test.

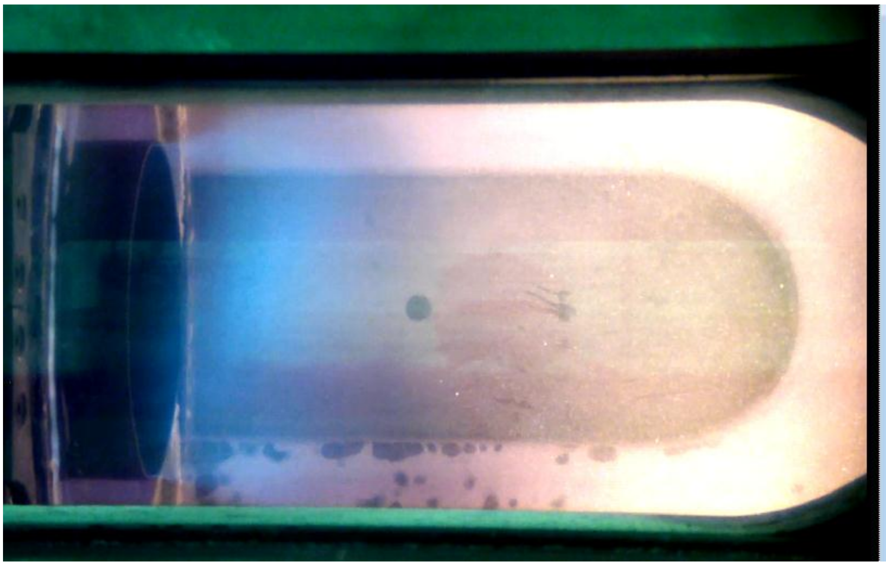


Figure 15: 23rd April. Configuration 3.3. 500kWth axial syngas flame

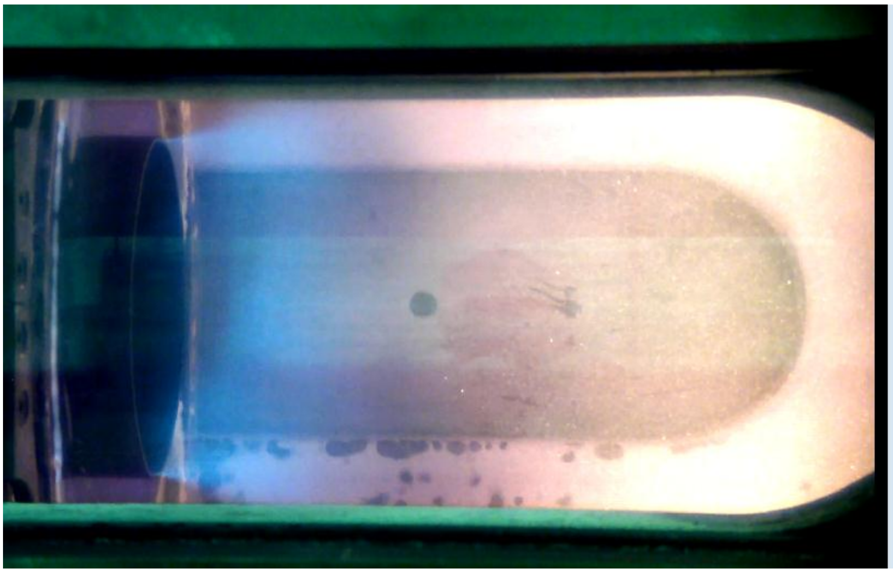


Figure 16: 23rd April. Configuration 3.3. 500kWth axial syngas flame

The raw exhaust high-speed pressure transducer measurements taken during this steady period can be seen in Figure 17 and shows pressure levels at approximately 6mb peak to peak which is comparable to the standard natural gas burner.

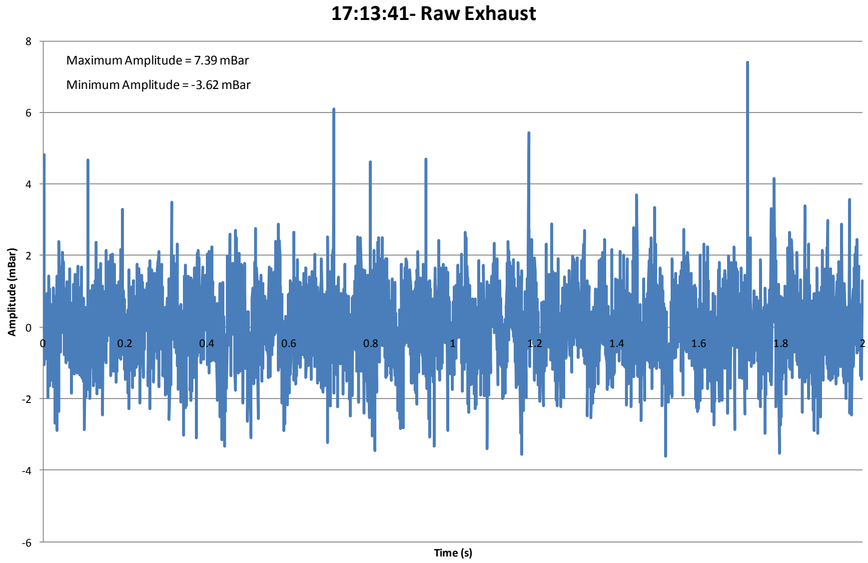


Figure 17: 23rd April. Configuration 3.3. Raw exhaust transducer data without pilot

The FFT spectra for the period captured in Figure 17 for the 3 pressure transducers (inlet, combustor and exhaust) can be seen in Figures 18, 19 and 20. The data supports the observation that the burner was acoustically stable during this operation, since there are no significant frequency spikes in the data.

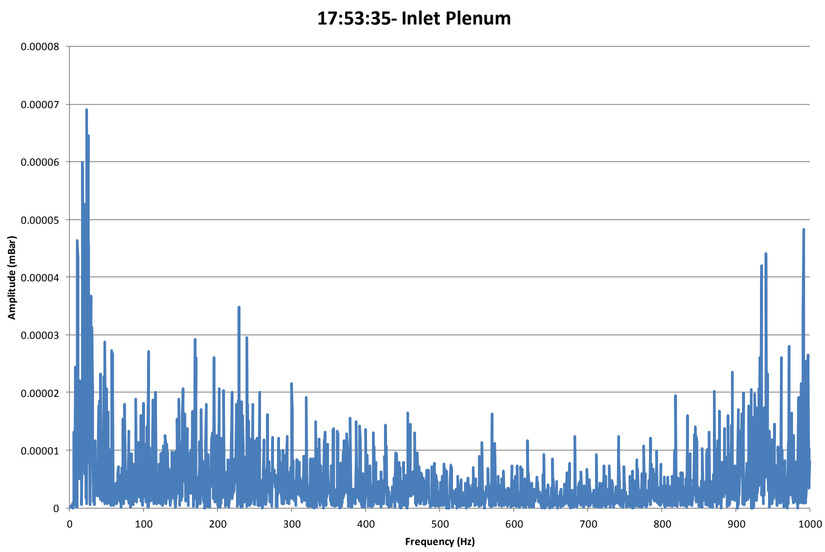


Figure 18: 23rd April 500kW. Configuration 3.3. Plenum FFT spectra

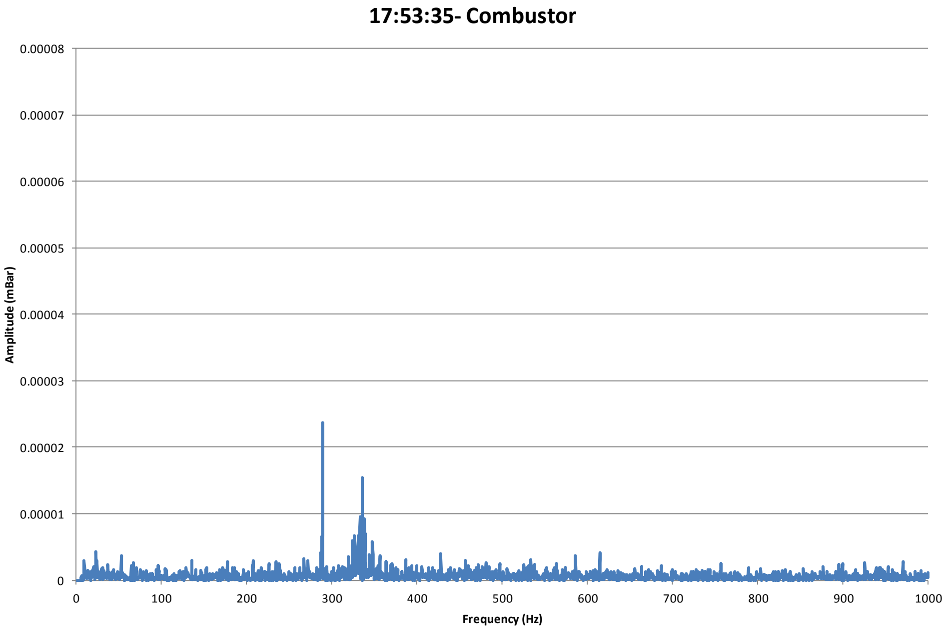


Figure 19: 23rd April 500kW. Configuration 3.3. Combustor FFT spectra

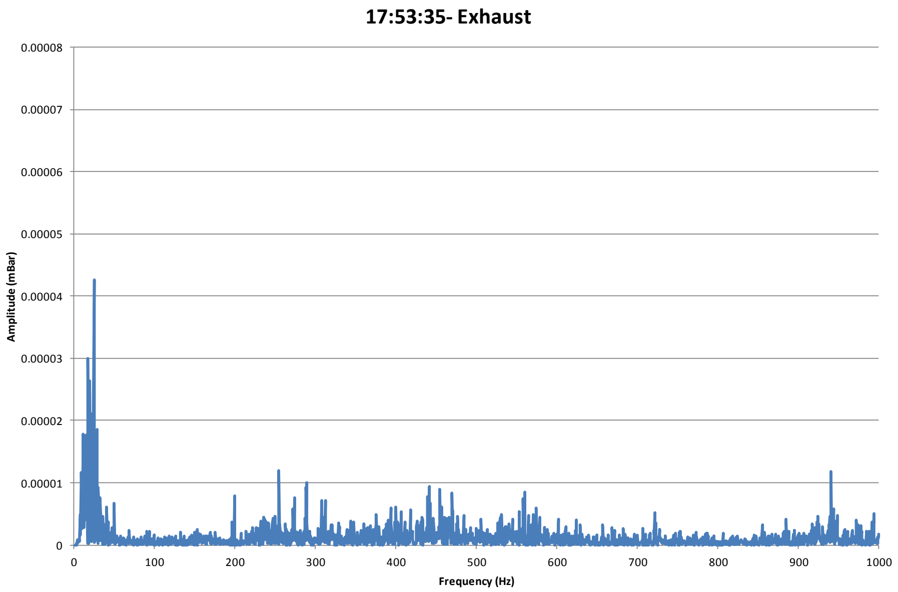


Figure 20: 23rd April 500kW. Configuration 3.3. Exhaust FFT spectra

After consideration of the data and performance in the previous tests, the decision was made by Ansaldo to use burner Configuration 3.2 as the preferred option for further testing to include elevated pressure and power at engine line representative conditions. Ansaldo provided the test conditions to be investigated which were calculated using real engine data from the AE64.3a Gas Turbine and scaled based on the criteria of the engine characteristic, M(√T)/P value. The conditions can be seen in Table 2 and Figure 21. BL means base load and MT means minimum turndown.

Table 2: 1.0 bara target engine operation conditions

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	Pressure (Bara)	Temp (K)	MrootT/P
Base Load	1	402.00	326.00	14.00	23.29	0.42	2.35	0.99	1	675	8.47
	2	402.00	326.00	15.00	21.73	0.46	2.20	0.99	1	675	8.47
	3	402.00	326.00	16.10	20.25	0.49	2.05	0.99	1	675	8.47
	4	402.00	326.00	17.40	18.74	0.53	1.89	0.99	1	675	8.47
70% Base Load	5	361.00	334.00	13.80	24.20	0.41	2.45	1.01	1	634	8.41
	6	361.00	334.00	14.70	22.72	0.44	2.30	1.01	1	634	8.41
	7	361.00	334.00	15.70	21.27	0.46	2.15	1.01	1	634	8.41
	8	361.00	334.00	16.90	19.76	0.50	2.00	1.01	1	634	8.41
MT	9	331.00	346.00	13.10	26.41	0.37	2.67	1.05	1	604	8.50
	10	331.00	346.00	13.90	24.89	0.40	2.52	1.05	1	604	8.50
	11	331.00	346.00	14.80	23.38	0.42	2.36	1.05	1	604	8.50
	12	331.00	346.00	15.80	21.90	0.45	2.21	1.05	1	604	8.50

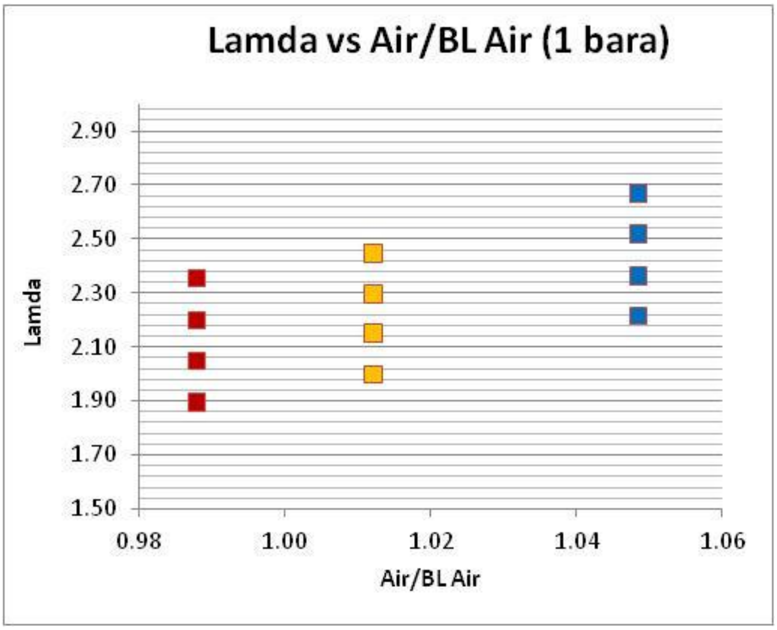


Figure 21: 1.0 bara target engine operation conditions

The experimental conditions based on the rig data can be seen in Figure 22. The circled areas show the test points met for each of the conditions approaching base load, 70% base load and minimum turndown; the steady periods are thus during the test points themselves. The gas analysis data can be seen in Figure 23, note the increase in NOx as the fuel flow rate (hence power) is increased.

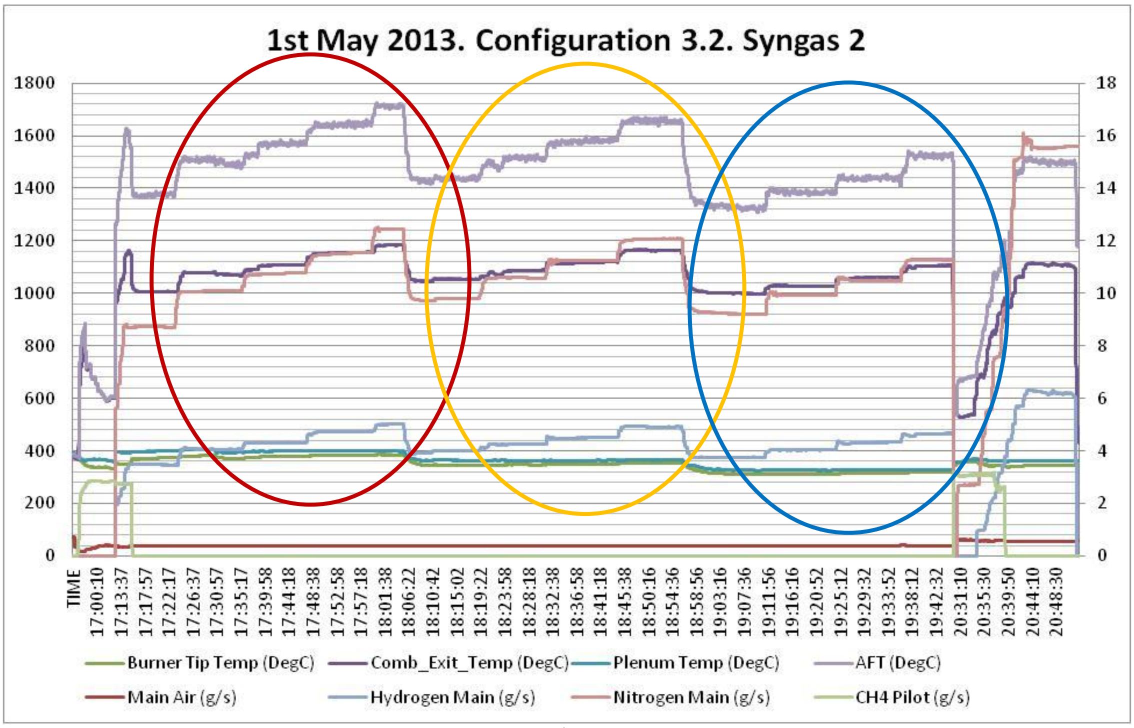


Figure 22: 1st May rig conditions

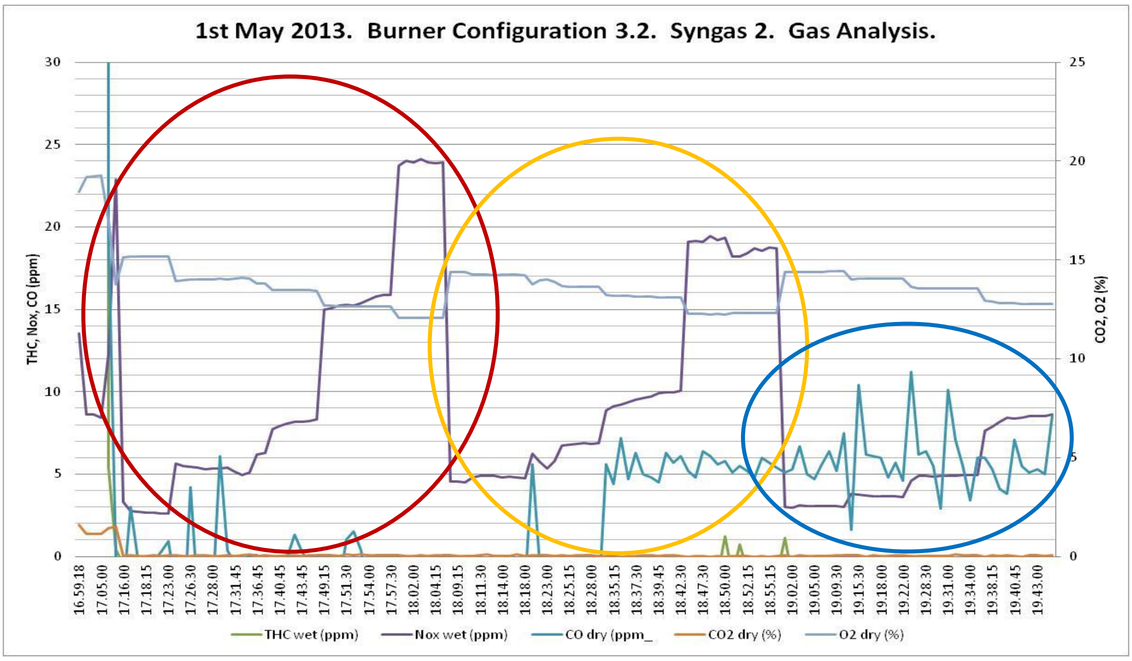


Figure 23: 1st May gas analysis

The actual achieved experimental test points and associated burner conditions are illustrated in Table 3 and Figure 24. Note the differences between this and Table 3 / Figure 24, which are attributed to the challenge of meeting the exact test point conditions at the lower limit of facility turndown.

Table 3: 1.0 bara actual experimental conditions

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	AFT C	Nox ppmV wet	Pressure (Bara)	Temp (K)	MrootT/P
	1	403	330	14.15	23.32	0.42	2.36	1.000	1514	4	1	676	8.58
	2	398	335	15	22.33	0.44	2.26	1.015	1570	8	1	671	8.68
Base	3	400	330	16.2	20.37	0.49	2.06	1.000	1640	15	1	673	8.56
Load	4	400	330	17.4	18.97	0.52	1.92	1.000	1714	25	1	673	8.56
	5	365	340	13.8	24.64	0.40	2.49	1.030	1428	4.7	1	638	8.59
	6	363	340	14.8	22.97	0.43	2.32	1.030	1500	6.4	1	636	8.57
70% Base	7	364	330	15.7	21.02	0.47	2.13	1.000	1580	9	1	637	8.33
Load	8	365	330	16.9	19.53	0.51	1.97	1.000	1654	19	1	638	8.34
	9	331	350	13	26.92	0.37	2.72	1.061	1338	3	1	604	8.60
	10	327	350	14	25.00	0.40	2.53	1.061	1379	3.8	1	600	8.57
	11	328	350	14.7	23.81	0.42	2.41	1.061	1430	4.8	1	601	8.58
MT	12	328	345	15.8	21.84	0.45	2.21	1.045	1529	8.6	1	601	8.46

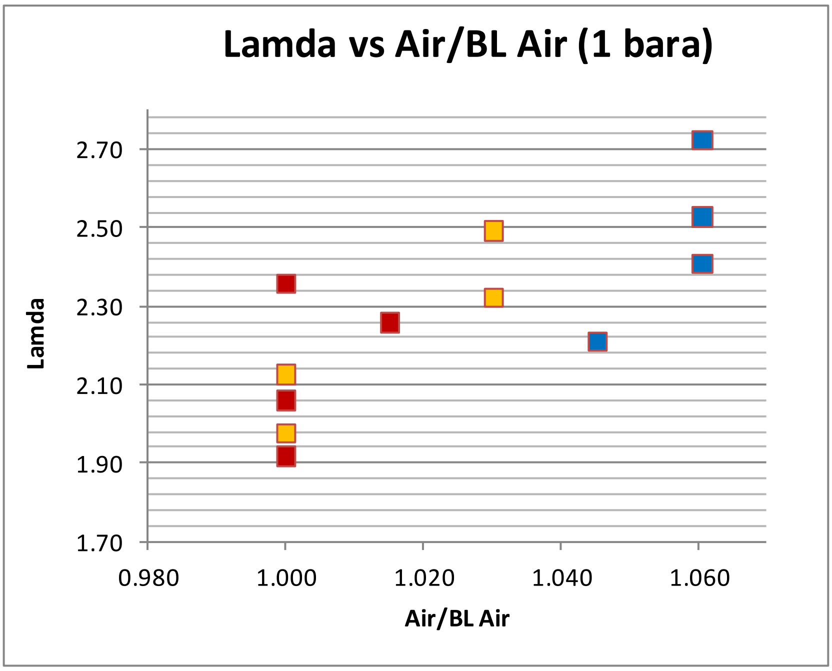


Figure 24: 1.0 bara Experimental Conditions

It was difficult to match the desired engine conditions exactly due to the sensitivity of the air compressor and control valves used on the facility which struggled with increments of 10g/s when designed for a maximum air flow of 5000g/s, although the data produced is sufficient to define the operation and emissions of the burner. The relationship between NOx and

Adiabatic Flame temperature is consistent for the conditions tested and is shown in Figure 25.

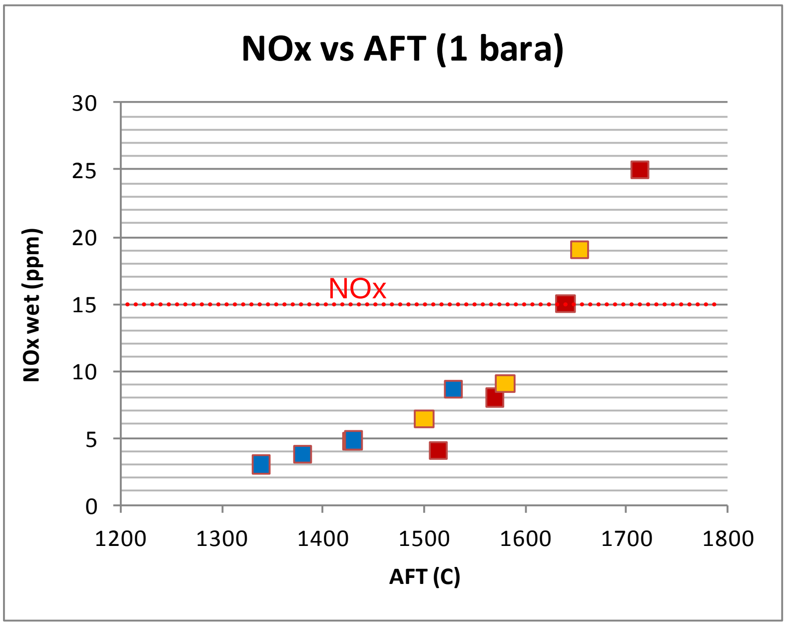


Figure 25: NOx vs AFT (calculated based on fuel flow and composition) at 1.0 bara.

The 15ppm NOx limit imposed by Ansaldo was exceeded at the base load and 70% base load conditions (highlighting the requirement for NOx reduction techniques such as steam, CO_2 or N_2 injection). With a small amount of fuel remaining, the burner was then driven to the 1.5 bara condition which was stable between 20:45 and 20:50 as seen in Figure 26.

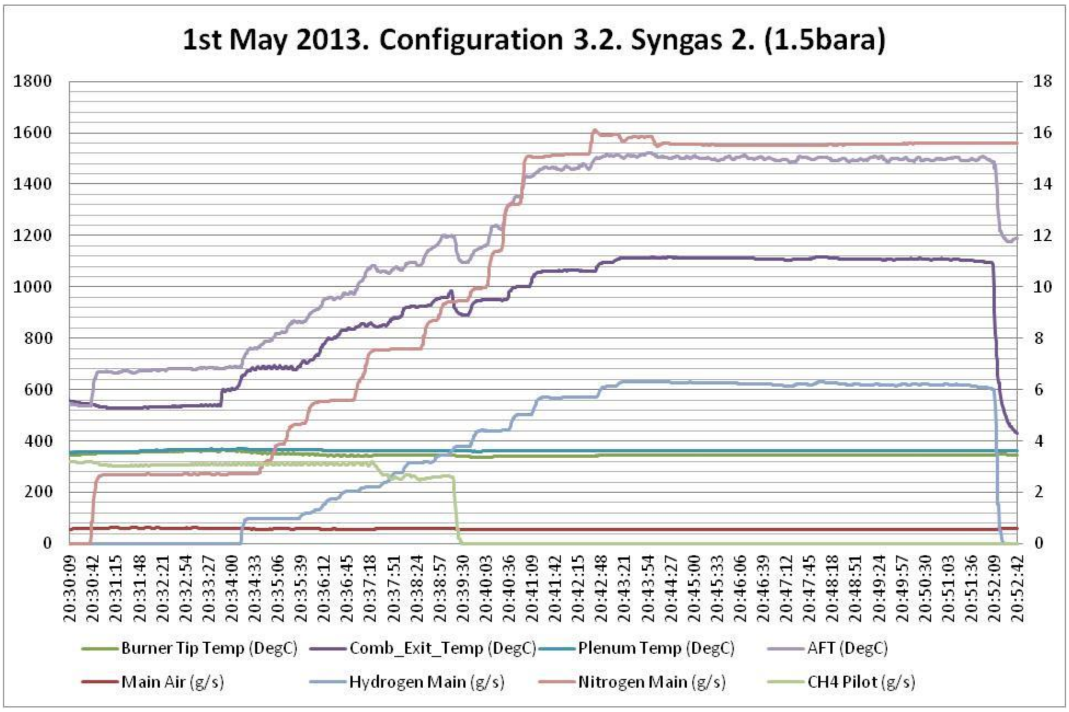


Figure 26: 1st May 1.5bar Rig Conditions

The gas analysis for this period can be seen in Figure 27, during which time the NOx measurement was stable at 6ppm.

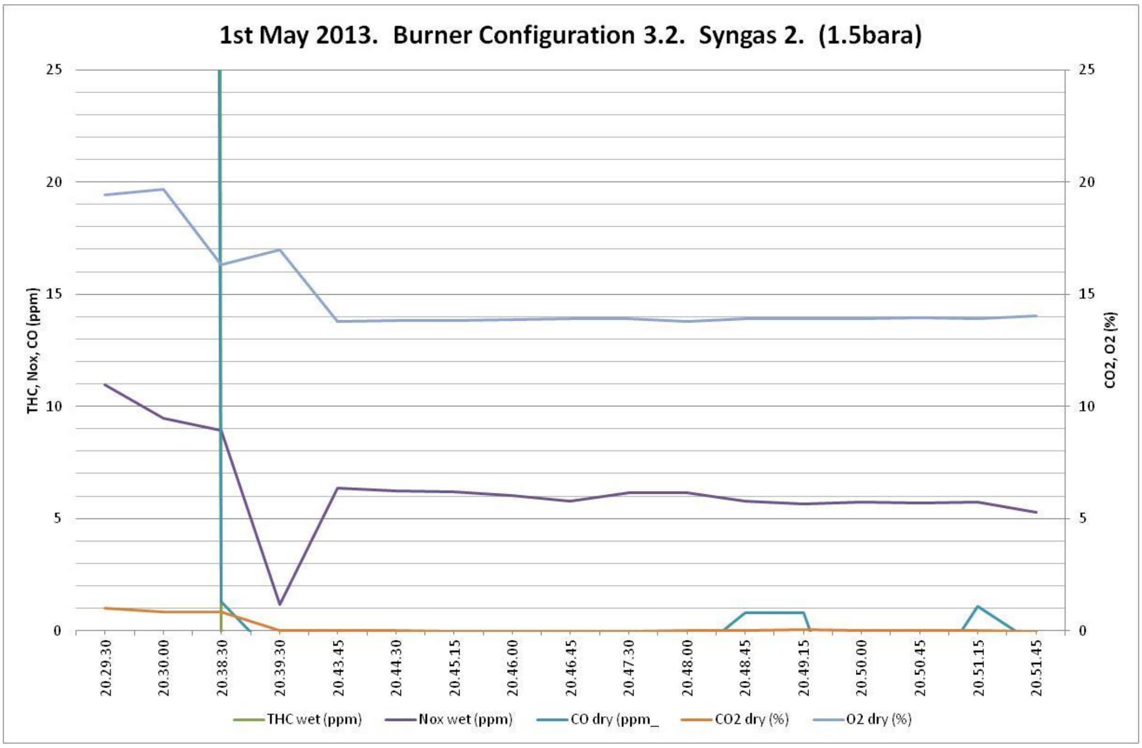
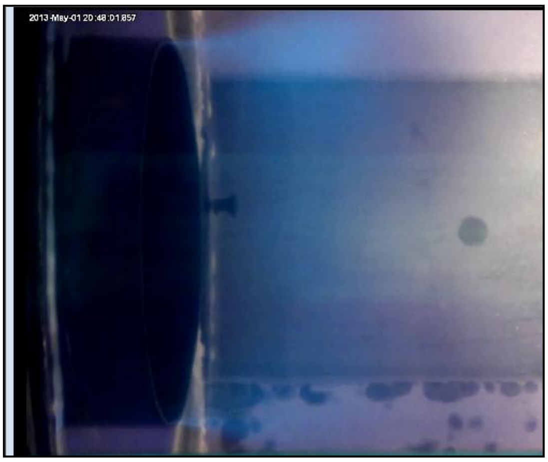


Figure 27: 1st May 1.5bar Gas Analysis

Images of the flame during this stable period can be seen in Figure 28 which show a symmetrical and homogeneous flame. Overall, operation was stable at this pressure and it was decided that this configuration could be used for further characterisation at engine line conditions at 1.5 and 2.0 bara.



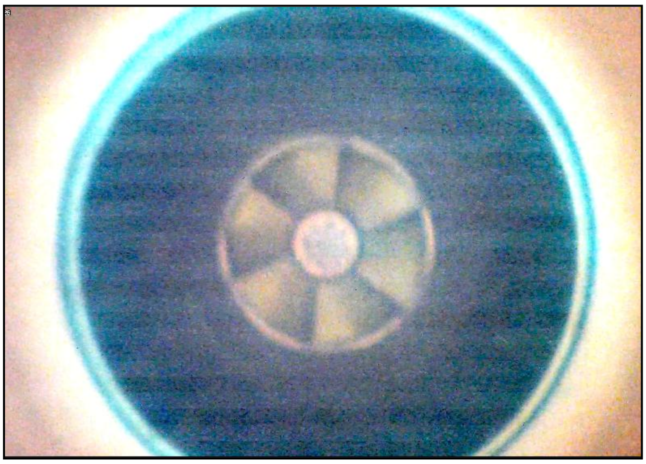


Figure 28: 1st May. 1.5 bara Axial and Radial Flame Images

2nd May 2013 - syngas burner Configuration 3.2. Syngas 2, 1.5 bara and 2.0 bara

Ansaldo provided the test conditions to be investigated which can be seen in Table 4 and Figure 29.

Table 4: 1.5 bara target engine operation conditions

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	Pressure (Bara)	Temp (K)	MrootT/P
Base Load	1	402	482	20.8	23.1731	0.426788	2.343082	1.000	1.5	675	8.35
	2	402	482	22.3	21.6143	0.457566	2.185475	1.000	1.5	675	8.35
	3	402	482	23.9	20.1674	0.490396	2.039167	1.000	1.5	675	8.35
	4	402	482	24.15	19.9586	0.495526	2.018058	1.000	1.5	675	8.35
70% Base Load	5	361	494	20.4	24.2157	0.408413	2.448502	1.025	1.5	634	8.29
	6	361	494	21.8	22.6606	0.436441	2.291259	1.025	1.5	634	8.29
	7	361	494	23.3	21.2017	0.466472	2.143753	1.025	1.5	634	8.29
	8	361	494	23.8	20.7563	0.476482	2.098716	1.025	1.5	634	8.29
MT	9	331	511	20.5	24.9268	0.396761	2.520407	1.060	1.5	604	8.37
	10	331	511	20.65	24.7458	0.399664	2.502099	1.060	1.5	604	8.37

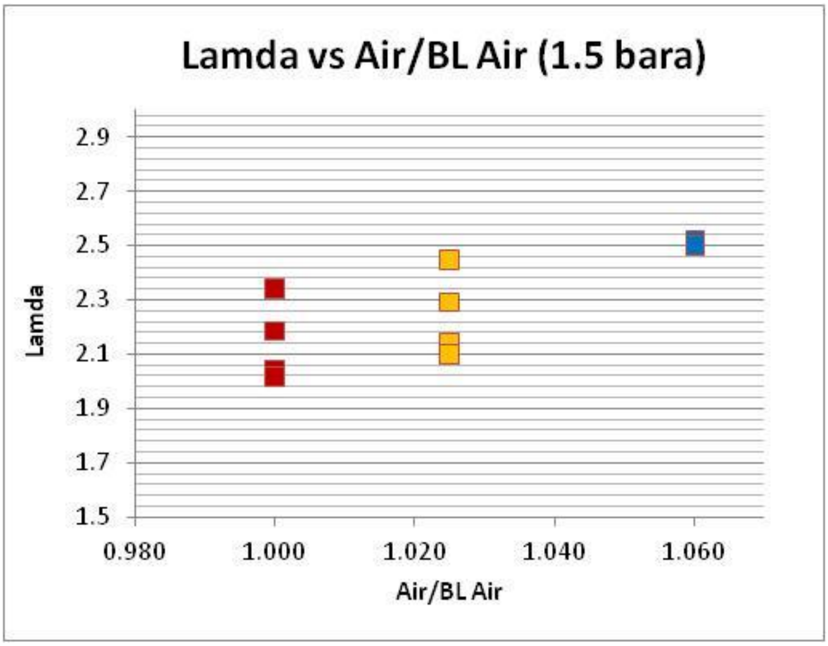


Figure 29: 1.5 bara target engine operation conditions

The experimental conditions can be seen in Figure 30. The circled areas show the test points met for each of the conditions approaching base load, 70% base load and minimum turndown. The gas analysis data can be seen in Figure 31.

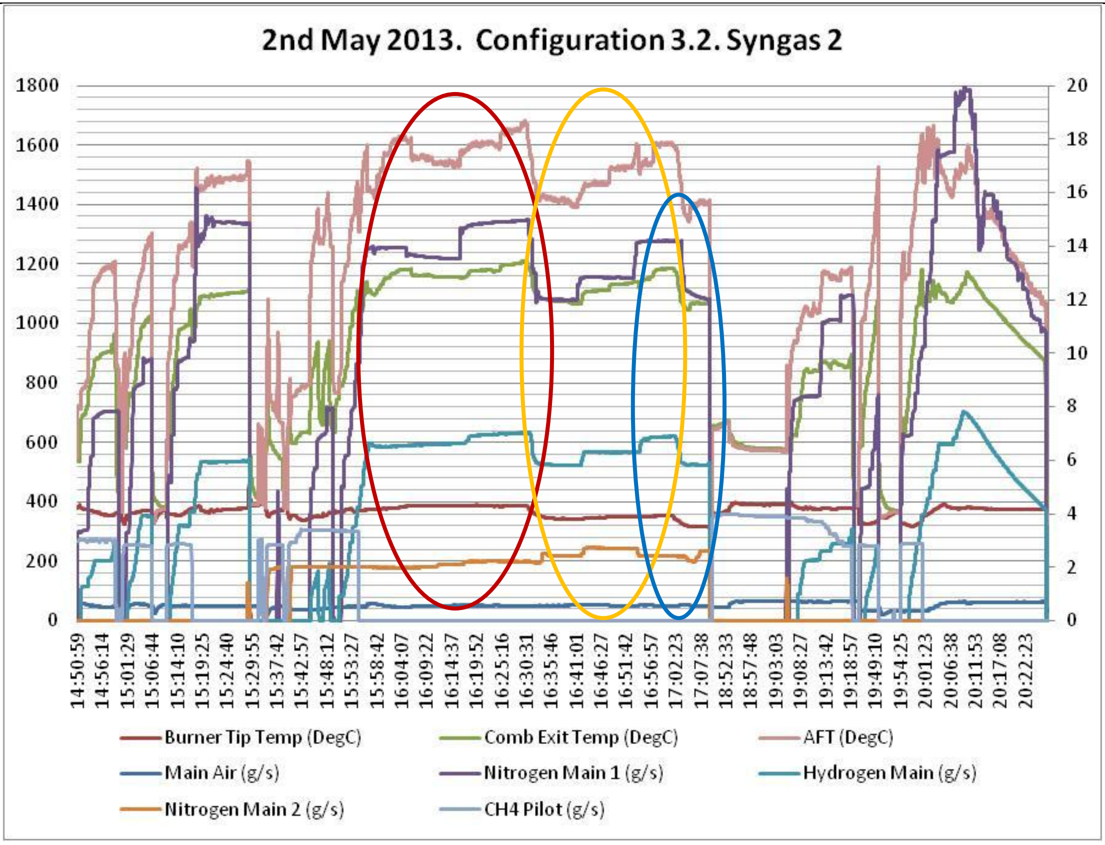


Figure 30: 2nd May rig conditions

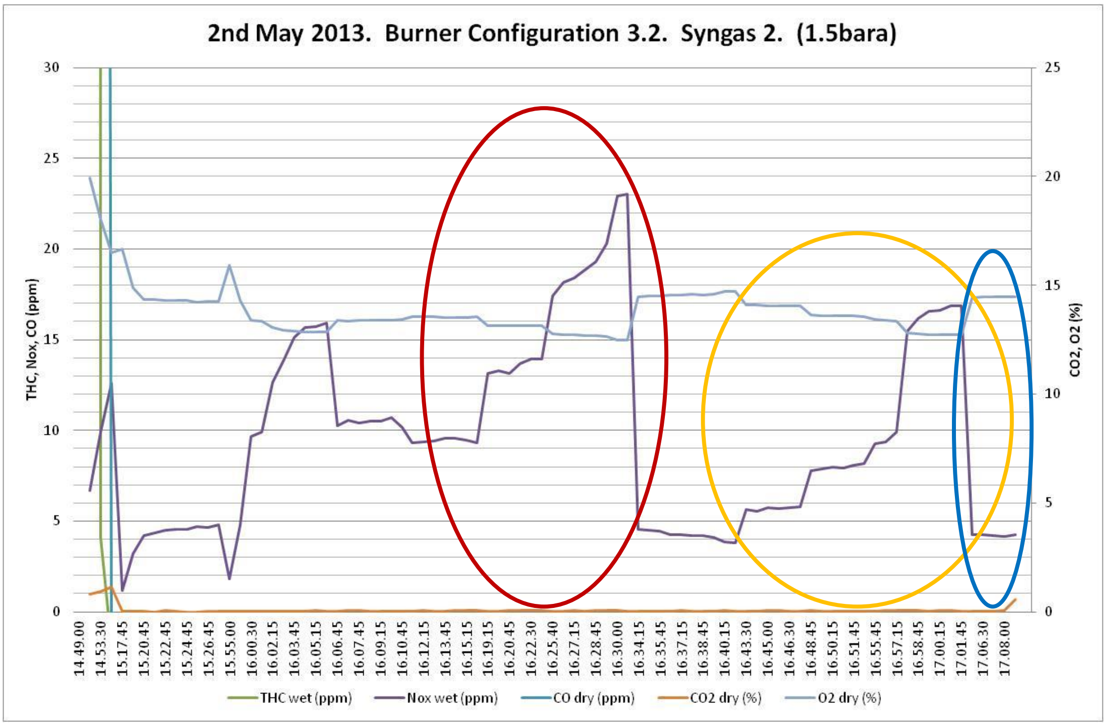


Figure 31: 2nd May Gas Analysis

The actual experimental test points and associated burner conditions are illustrated in Table 5, Figure 32 and 33. The 1.5 bara test point from the 1st May is also plotted here.

Table 5: 1.5 bara actual experimental conditions

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	AFT C	Nox ppmV wet	Pressure (Bara)	Temp (K)	MrootT/P
Base Load	1	394	500	20.8	24.04	0.41	2.43	1.037	1479	4.5	1.5	667	8.61
	2	403	490	22.3	21.97	0.45	2.22	1.017	1561	10.6	1.5	676	8.49
	3	400	485	23.9	20.29	0.49	2.05	1.006	1650	18	1.5	673	8.39
70% Base Load	4	365	500	20.4	24.51	0.40	2.48	1.037	1421	4.5	1.5	638	8.42
	5	364	480	21.8	22.02	0.45	2.23	0.996	1517	7.8	1.5	637	8.08
	6	363	480	23.3	20.60	0.48	2.08	0.996	1603	16.5	1.5	636	8.07
MT	7	330	500	20.5	24.39	0.41	2.47	1.037	1397	4.2	1.5	603	8.19

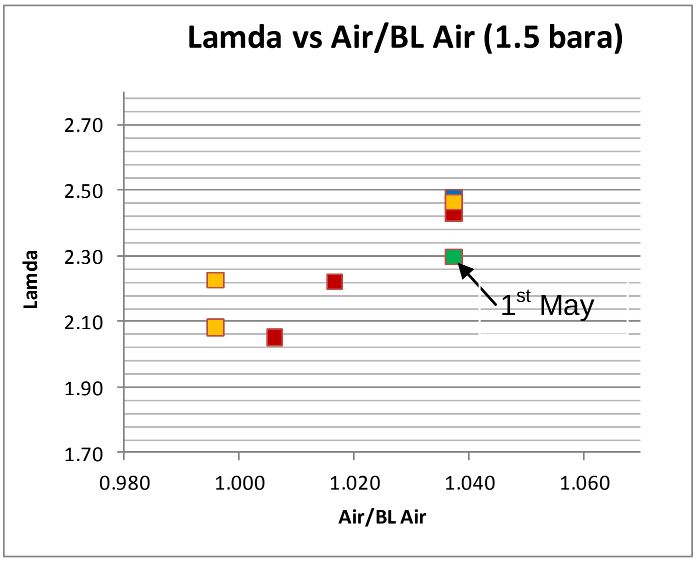


Figure 32: 1.5 bara actual experimental conditions

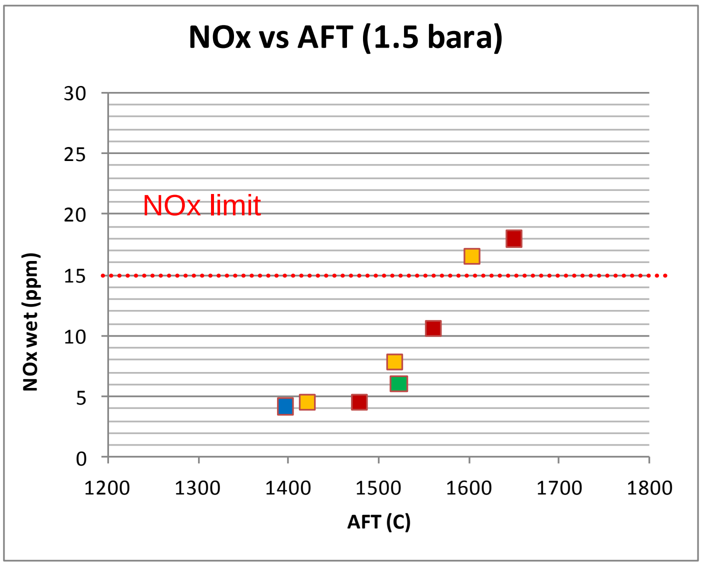


Figure 33: NOx vs AFT (calculated based on fuel flow and composition) at 1.5 bara.

As with the 1.0 bara case, it can be seen from Figure 33 that the 15ppm NOx limit imposed by Ansaldo was exceeded at the base load and 70% base load conditions. Despite the high NOx it was agreed that this burner was stable at the conditions tested and there had been no data to indicate a risk of flashback at 1.5 bara, so it was decided to run up to the 2.0 bara condition. There was a limited supply of fuel remaining, so only 3 points were aimed for on this day. The target engine operating conditions can be seen in Table 6 and Figure 34.

Table 6: 2.0 bara target engine operation conditions

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	Pressure (Bara)	Temp (K)	MrootT/P
Base Load	11	402	643	28.1	22.8826	0.432207	2.313707	1.000	2	675	8.35
	12	402	643	30.1	21.3621	0.462969	2.159972	1.000	2	675	8.35
	13	402	643	32.4	19.8457	0.498345	2.006641	1.000	2	675	8.35

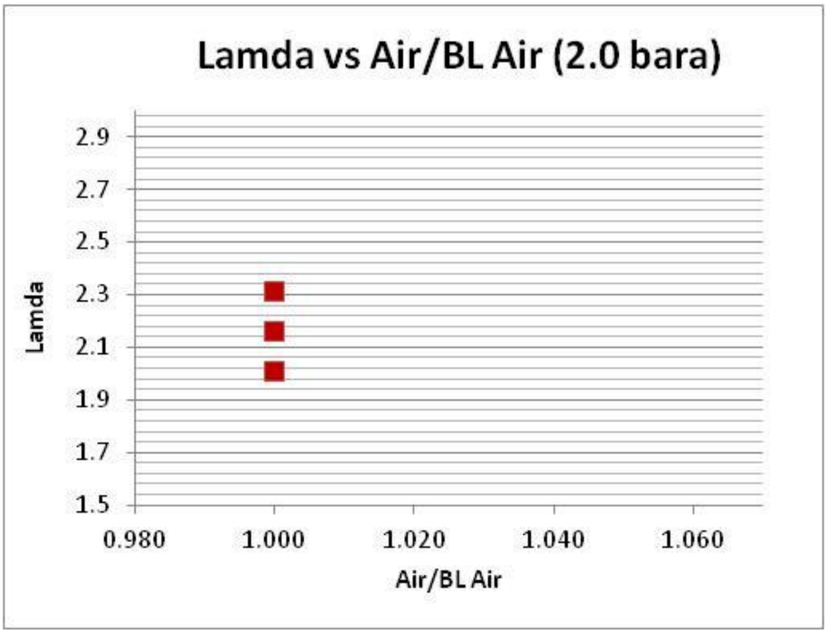


Figure 34: 2.0 bara target engine operation conditions

It proved challenging to drive the rig up to the 2.0 bara condition due to the nature of how the facility controls air flow and pressure. Unlike the fixed relationship with a gas turbine, the facility controls pressure and flow rate separately using compressor demand and a back pressure valve. Therefore, during the transition from light up to operating condition, which can be seen in Figure 35 and 36, the compressor demand and back pressure valve have to be constantly trimmed to ensure that the burner remains within its stable limit to prevent blow off or flashback. Note that 2 lines were used to provide fuel nitrogen, since the flow rate was now higher that what could realistically flow in a 1 inch pipe. The methane pilot was cut at the 1.0 bara (500kWth) condition and from this point the burner was driven up to the 1.5 bara condition and then 2.0 bara condition with the premix syngas main alone. Ansaldo's preference would be to cut the pilot at the 2.0 bara condition, but initial attempts at keeping the pilot lit during the increasing pressure transition resulted in an increase in burner tip temperature, high combustor exit temperatures, high AFT and high NOx.

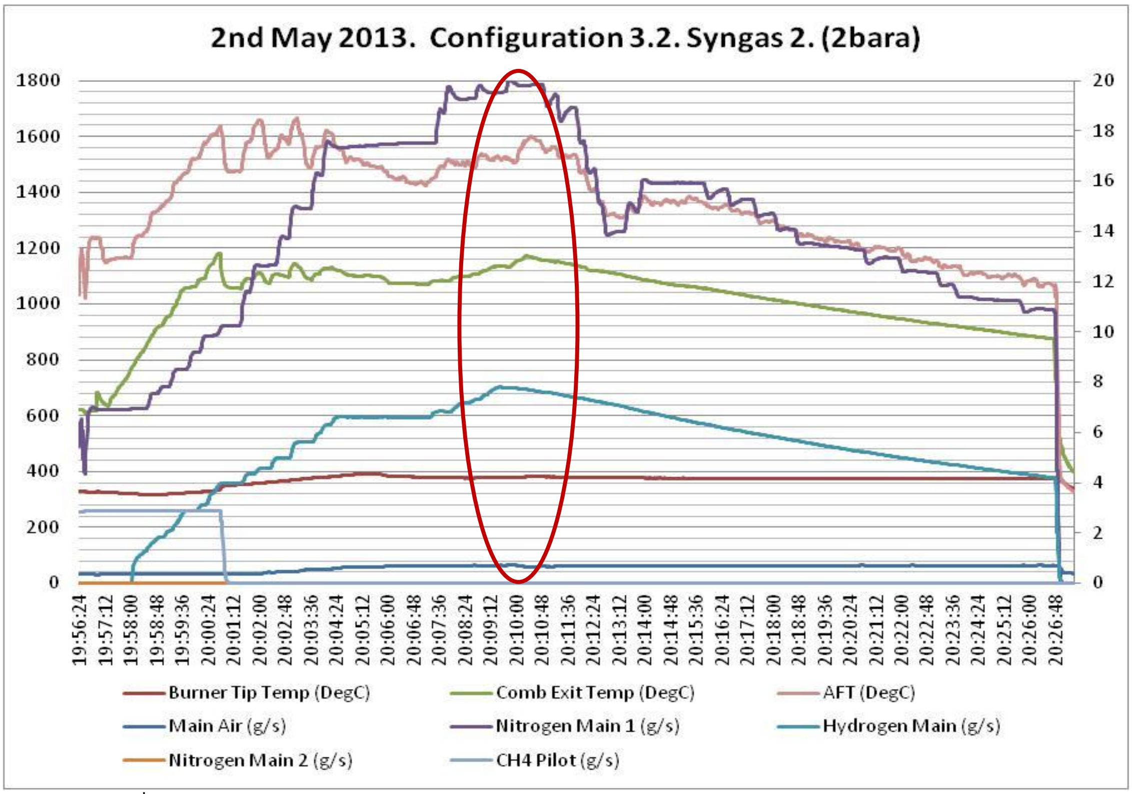


Figure 35: 2nd May. 2.0 bara Rig Conditions. The red ellipse denotes when the H_2 ran out.

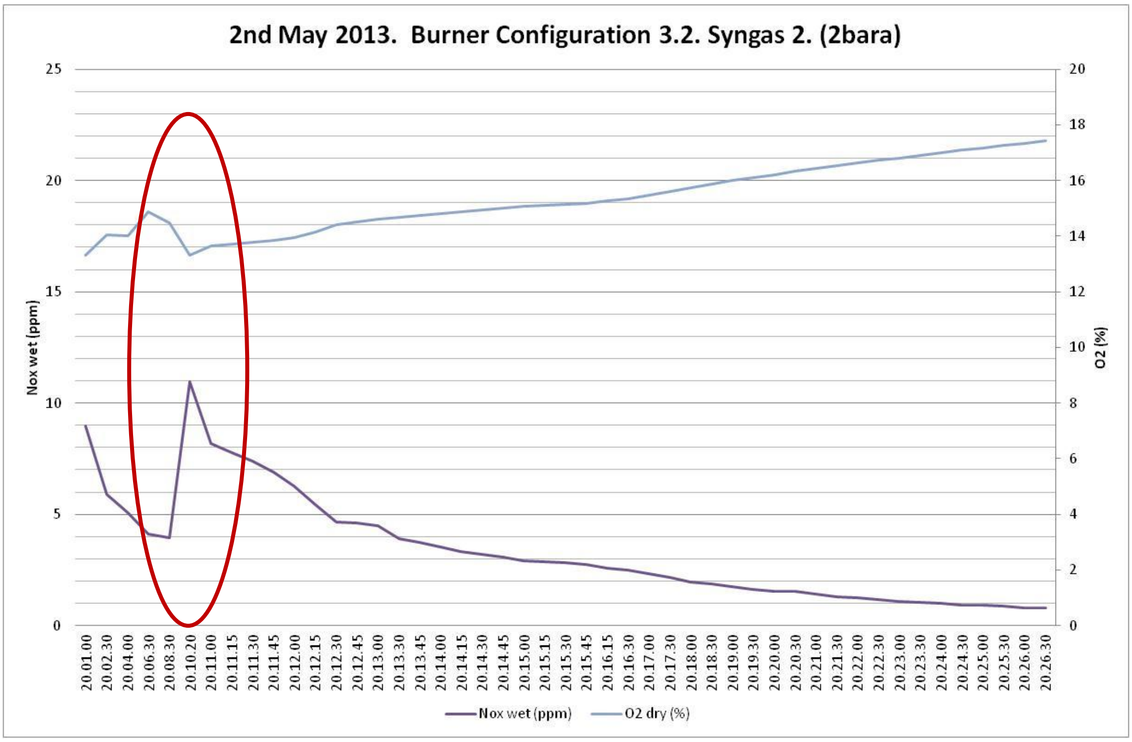


Figure 36: 2nd May. 2.0 bara Gas Analysis

For the condition reached the NOx was measured at 11ppm which is below the threshold set by Ansaldo. Only 2 test points were managed before the hydrogen supply was exhausted and it was decided that the burner was stable enough to replenish the hydrogen supply and continue testing at this pressure. Table 7 and Figures 37 & 38 show the actual experimental test points and rig conditions.

Table 7: 2.0 bara actual experimental conditions

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	AFT C	Nox ppmV wet	Pressure (Bara)	Temp (K)	MrootT/P
Base	8	396	580	27.5	21.09	0.47	2.13	0.902	1585	11	2	669	7.50
Load	8A	396	603	24.29	24.83	0.40	2.51	0.938	1450	4	2	669	7.80

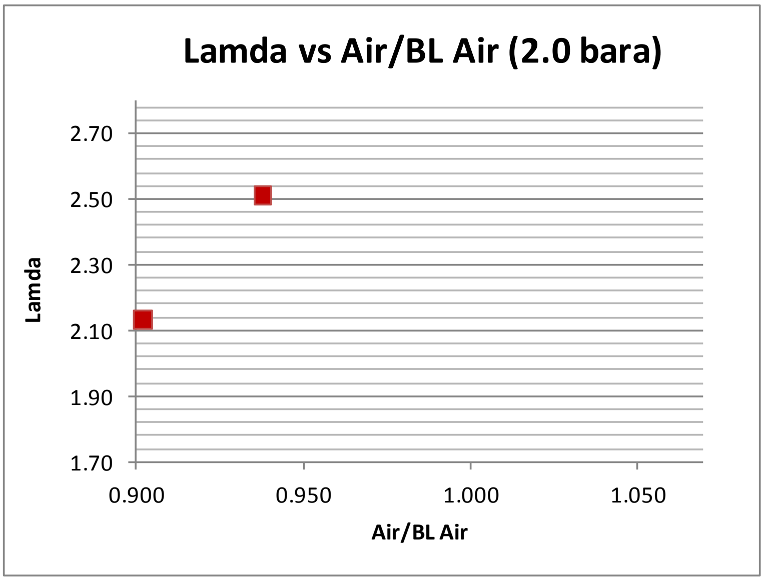


Figure 37: 2.0 bara actual experimental conditions

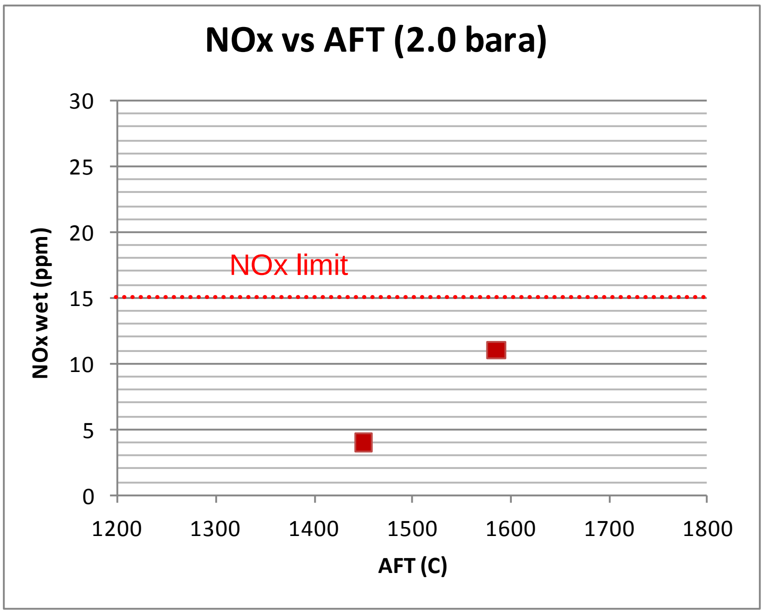


Figure 38: NOx vs AFT (calculated based on fuel flow and composition) at 2.0 bara

The AFR achieved before the fuel supply ran out was on the lean side of baseload and therefore the NOx measurements taken of 12ppm were are on the low side of what would be expected at base load and 2.0 bara. During the transient pressure period between 1.5 bara and 2.0 bara a strong instability which was audible in the control room was observed and is illustrated in Figure 39.

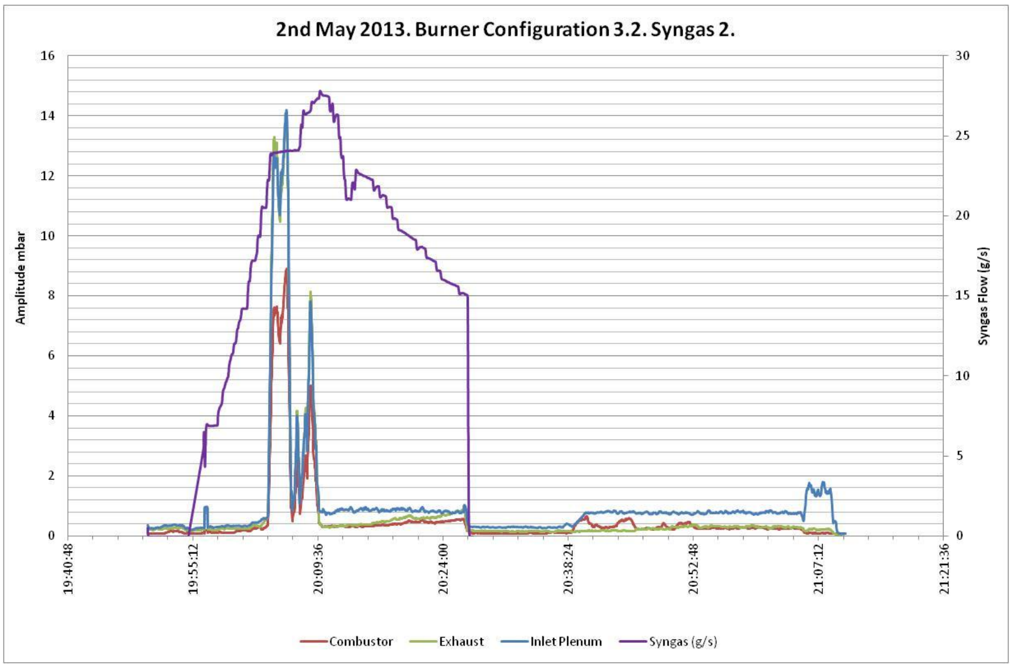


Figure 39: 2nd May. 2.0 bara pressure transducer measurements

The inlet and exhaust pressure transducers synchronised with the inlet plenum amplitude peaking at 14 mbar. During this period a precessing vortex structure was observed in the radial images rotating around the CBO which can be seen in Figure 40.

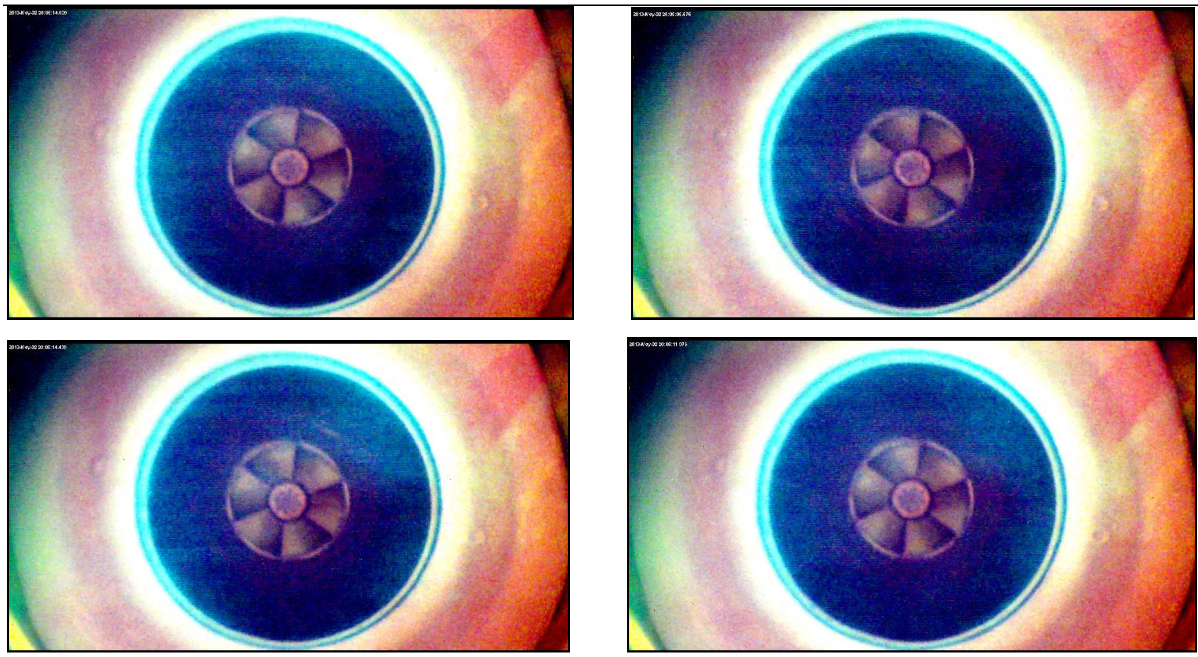


Figure 40: 2nd May. Structure Observed During Increasing Pressure Transient

29th May 2013 - Syngas Burner Configuration 3.2. Syngas 2. 2.0 bara

Ansaldo provided the test conditions to be investigated which can be seen in Table 8 and Figure 41.

Table 8: 2.0 bara target engine operation conditions

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	Pressure (Bara)	Temp (K)	MrootT/P
Base Load	1	400	643	27.7	23.213	0.426054	2.347118	1.000	2.0	673	8.34
	2	400	643	29.6	21.723	0.455278	2.196458	1.000	2.0	673	8.34
	3	400	643	31.8	20.2201	0.489117	2.044502	1.000	2.0	673	8.34
70% Base Load	4	365	659	27.2	24.2279	0.408206	2.449741	1.025	2.0	638	8.32
	5	365	659	29.0	22.7241	0.43522	2.297688	1.025	2.0	638	8.32
	6	365	659	31.0	21.2581	0.465235	2.14945	1.025	2.0	638	8.32
MT	7	330	682	25.8	26.4341	0.374138	2.672812	1.061	2.0	603	8.37
	8	330	682	27.3	24.9817	0.39589	2.525954	1.061	2.0	603	8.37
	9	330	682	29.0	23.5172	0.420543	2.377881	1.061	2.0	603	8.37

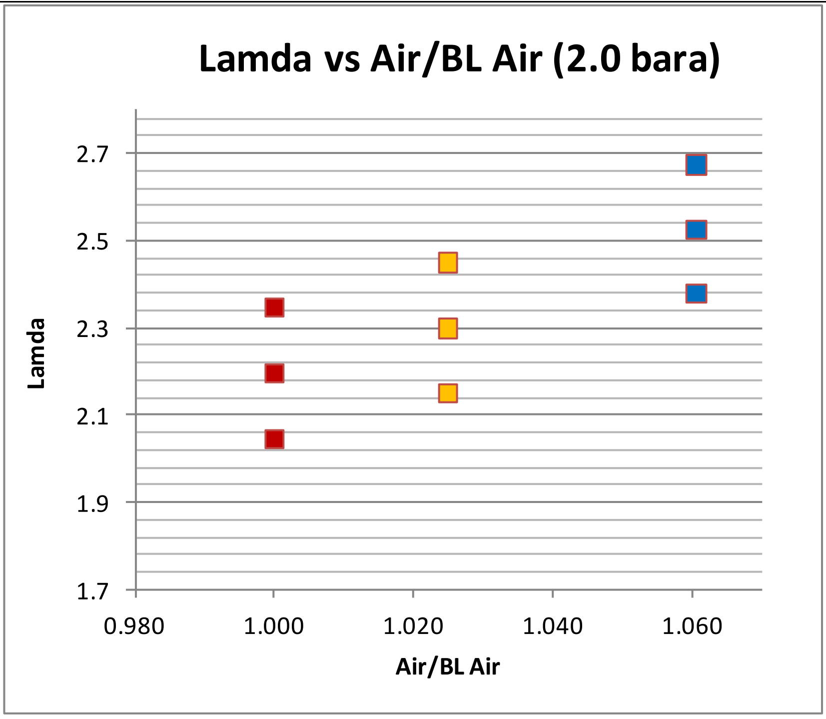


Figure 41: 2.0 bara target engine operation conditions

The experimental conditions can be seen in Figure 42. The circled areas show the test points met for each of the conditions approaching base load, 70% base load and minimum turndown; the steady periods are thus during the test points themselves. The gas analysis data can be seen in Figure 43.

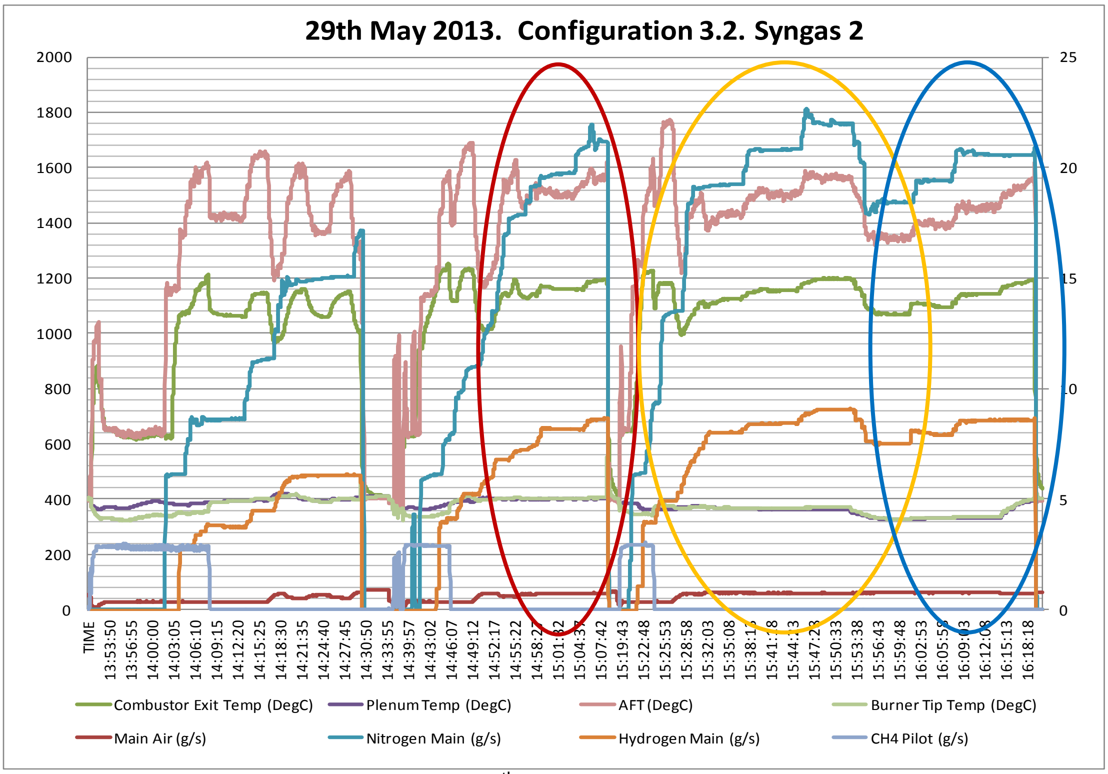


Figure 42: 29th May Rig Conditions

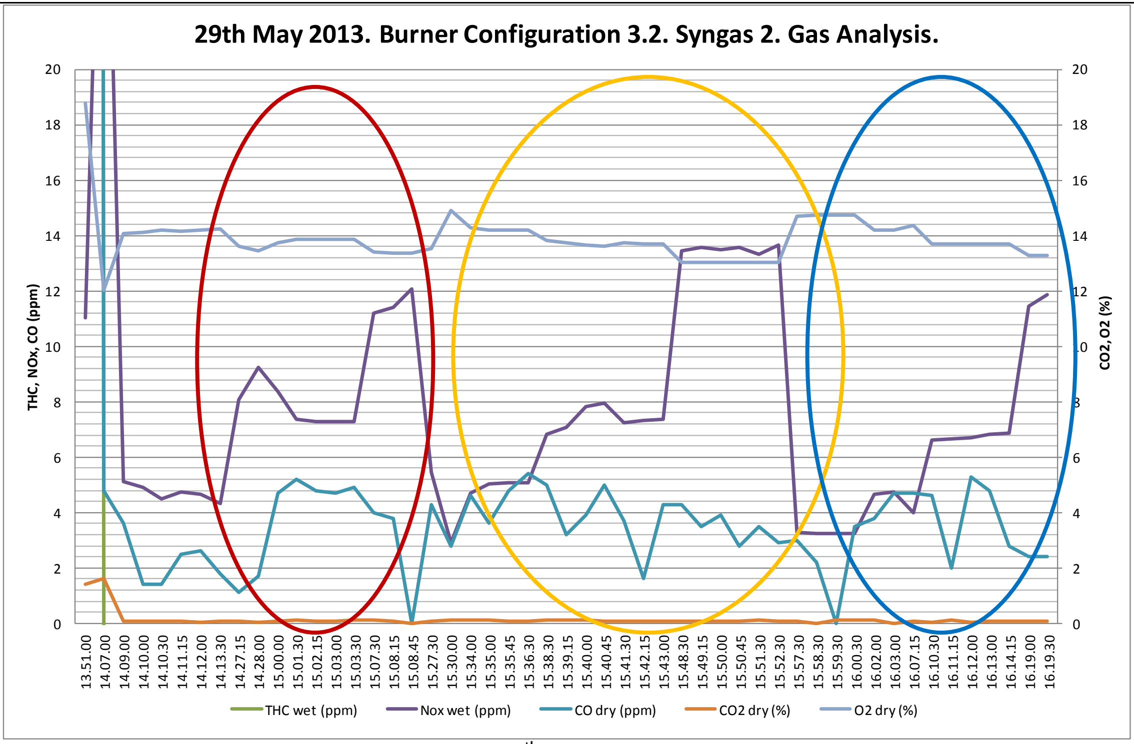


Figure 43: 29th May Gas Analysis

The experimental test points and associated burner conditions are illustrated in Table 9 and Figure 44 & 45.

Table 9: 2.0 bara actual experimental conditions

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	AFT C	Nox ppmV wet	Pressure (Bara)	Temp (K)	MrootT/P
	1	399	640	27.6	23.1884058	0.42650625	2.34463153	0.995	1510	8.4	2.05	672	8.09
Base	2	402	650	29.7	21.88552189	0.45189692	2.21289402	1.011	1566	11.4	2.09	675	8.08
Load	3	FLASHBACK											
	4	368	670	27.2	24.63235294	0.40150448	2.49063225	1.042	1430	5.0	2.02	641	8.40
70% Base	5	364	670	29.0	23.10344828	0.42807463	2.33604128	1.042	1499	7.3	2.04	637	8.29
Load	6	362	660	31.0	21.29032258	0.4645303	2.15271209	1.026	1561	13.2	2.07	635	8.03
	7	329	680	25.8	26.35658915	0.37523824	2.66497362	1.058	1359	3.3	2.08	602	8.02
	8	330	680	27.3	24.90842491	0.39705441	2.5185465	1.058	1397	4.5	2.12	603	7.88
MT	9	331	680	29.0	23.44827586	0.42177941	2.37090757	1.058	1453	6.6	2.10	604	7.96

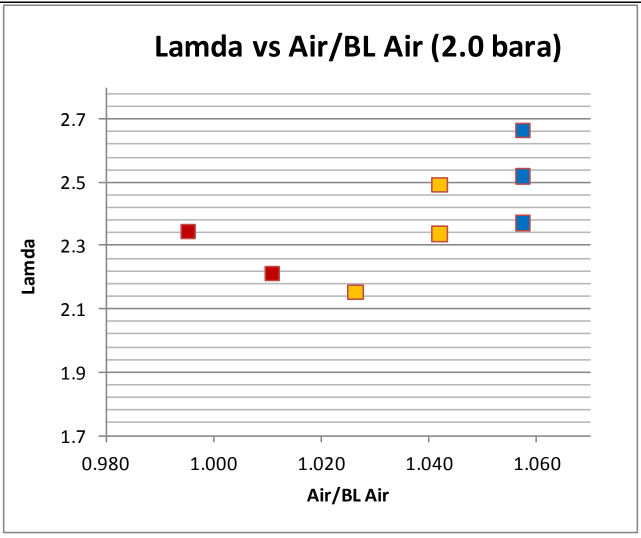


Figure 44: 2.0 bara actual experimental conditions

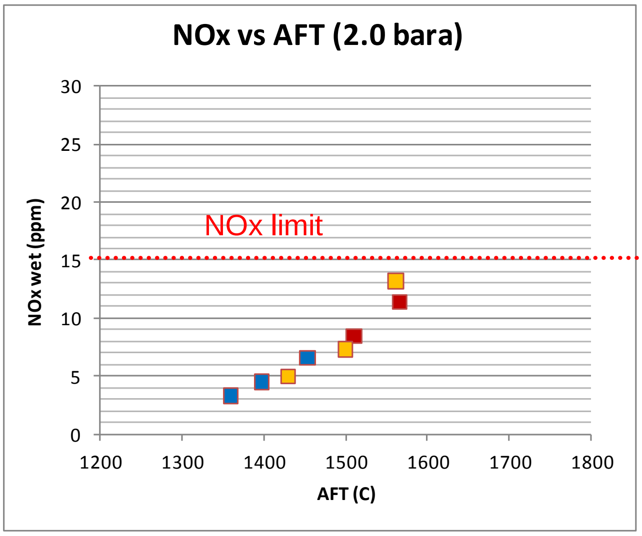


Figure 45: NOx vs AFT (calculated based on fuel flow and composition) at 2.0 bara

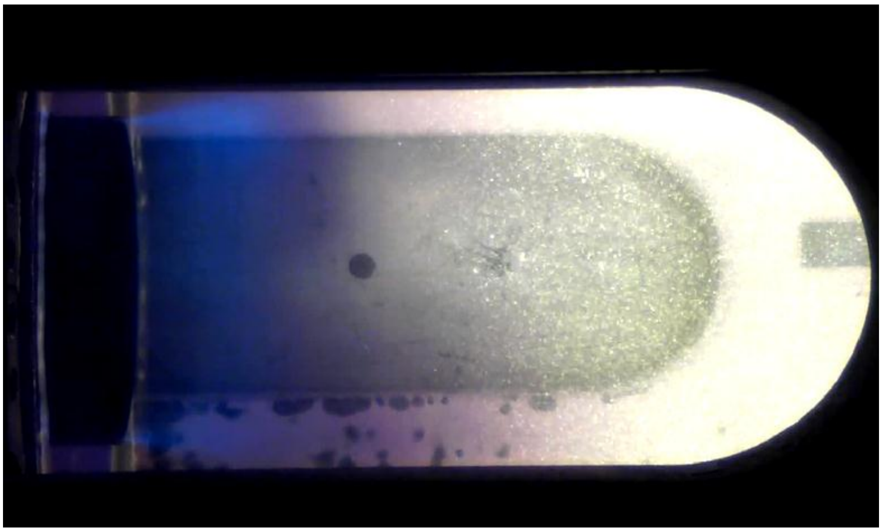


Figure 46: 2.0 bara stable flame during test point 6

The flame appeared stable (see Figure 46) at all test points except test point 3 which is baseload at which point the flame flashed back. Unfortunately, there did not seem to be any corresponding early indicators of flashback such as increasing burner tip temperatures or acoustic abnormalities. Also it was not clear as to the mode of the flashback e.g. boundary layer or sheer layer.

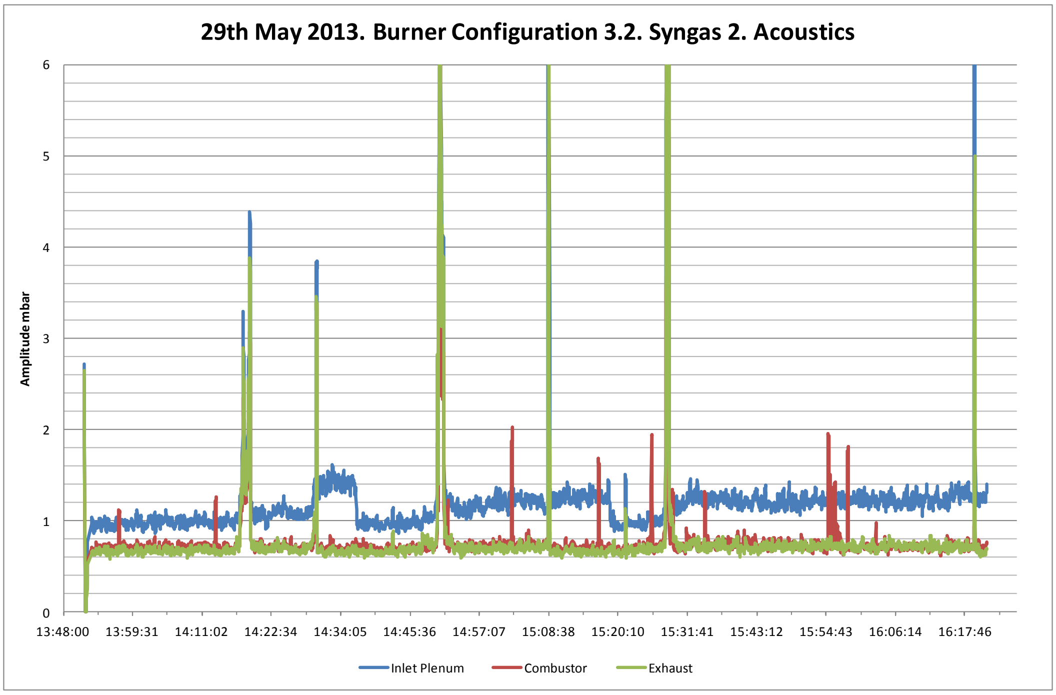


Figure 47: 2.0 bara pressure transducer amplitudes during the tests

The dynamic pressure transducer logs are shown in Figure 47. It can be seen that there are several high amplitude peaks associated with increasing pressure transients and flashback events at this operating pressure. It was therefore apparent that the increase in operating pressure from 1.5 to 2.0 bara was starting to show adverse effects on burner operation using this configuration.

30th May 2013 - Syngas Burner Configuration 3.2a. Syngas 2. 2.0 bara

After review of the operating data and experience, Ansaldo requested that the CBO be changed to one with a 25% reduction in exit area (RDA 25). The 2.0 bara test conditions were repeated and the experimental conditions can be seen in Figure 48 and the gas analysis in Figure 49.

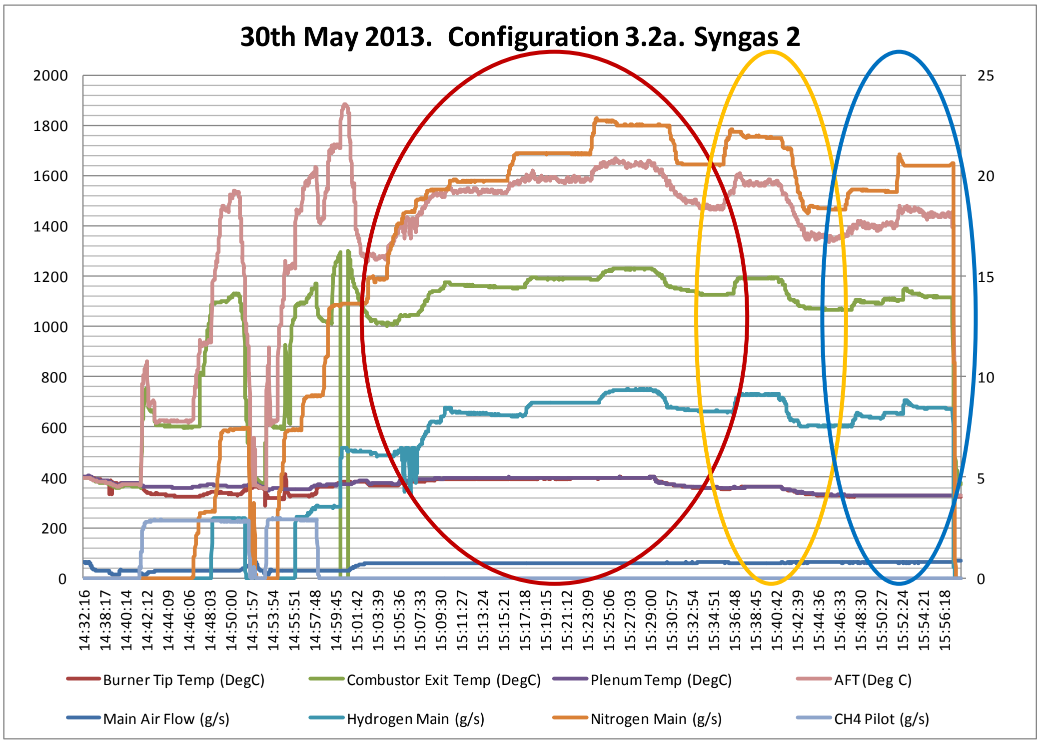


Figure 48: 30th May rig conditions at 2.0 bara. Configuration 4.2

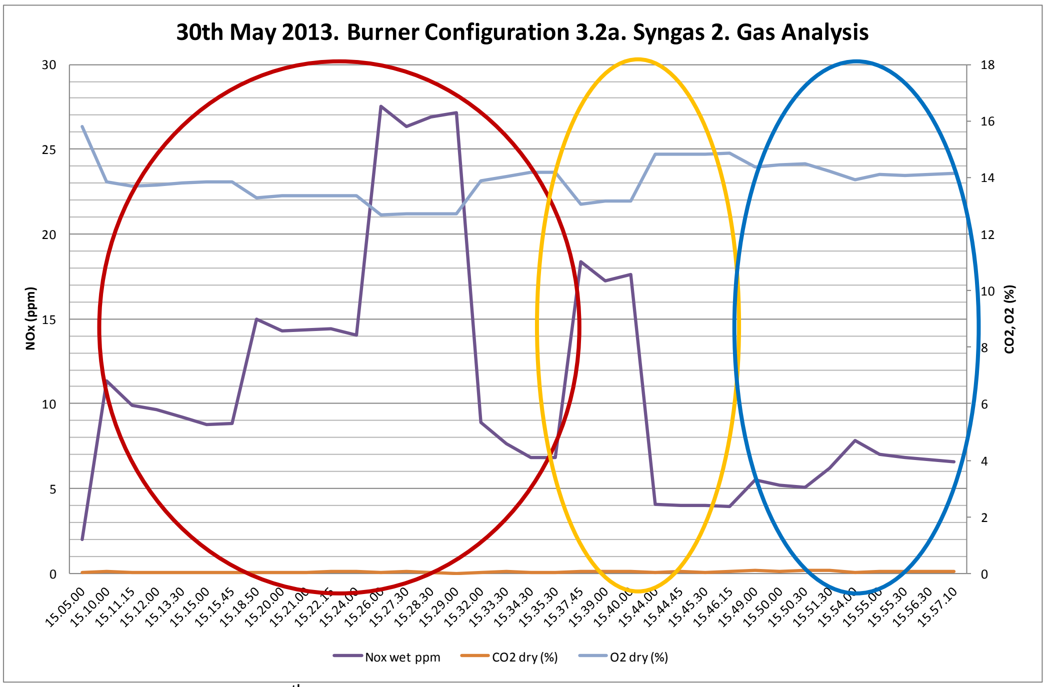


Figure 49: 30th May gas analysis at 2.0 bara. Configuration 4.2

The experimental test points and associated burner conditions are illustrated in Table 10 and Figures 50 & 51.

Table 10: 2.0 bara actual experimental conditions. Configuration 4.2

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	AFT C	Nox ppmV wet	Pressure (Bara)	Temp (K)	MrootT/P
Base Load	1	398	640	27.7	23.10469314	0.42805156	2.33616715	0.995	1543	9.85	1.99	671	8.33
	2	398	650	29.7	21.88552189	0.45189692	2.21289402	1.011	1592	14.0	2.05	671	8.21
	3	399	650	31.8	20.44025157	0.48384923	2.06675951	1.011	1648	26.4	2.10	672	8.02
70% Base Load	4	Missed Out Due to Fuel Usage Concerns											
	5	367	660	29.0	22.75862069	0.43456061	2.30117499	1.026	1509	9.0	2.06	640	8.11
	6	362	660	31.0	21.29032258	0.4645303	2.15271209	1.026	1579	17.3	2.09	635	7.96
MT	7	335	680	25.8	26.35658915	0.37523824	2.66497362	1.058	1347	4.1	2.01	608	8.34
	8	328	680	27.3	24.90842491	0.39705441	2.5185465	1.058	1399	5.3	2.03	601	8.21
	9	329	680	28.8	23.61111111	0.41887059	2.38737221	1.058	1445	6.9	2.08	602	8.02

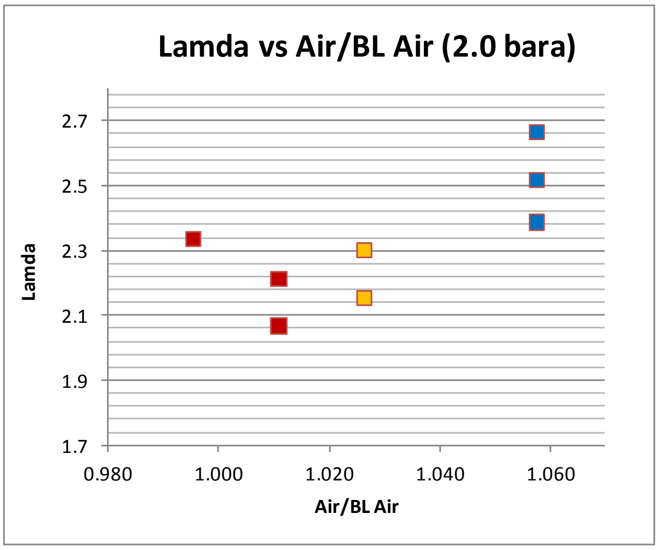


Figure 50: 2.0 bara actual experimental conditions. Configuration 4.2

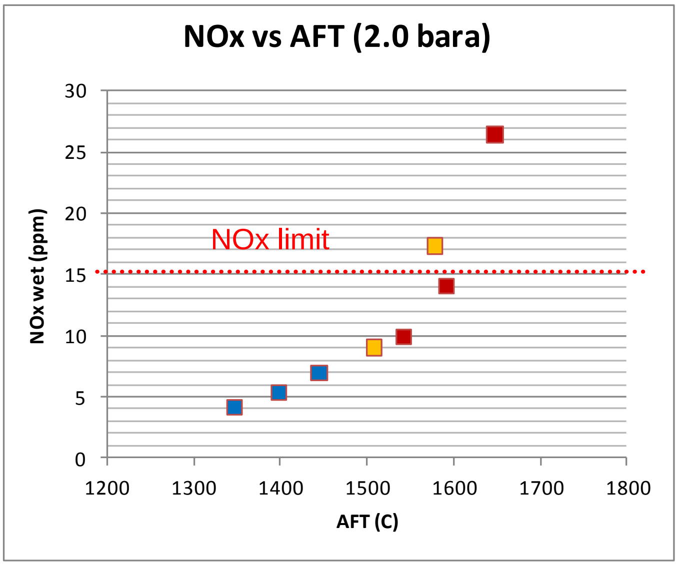


Figure 51: NOx vs AFT (calculated) at 2.0 bara. Configuration 4.2

It can be seen that with this new configuration it was possible to achieve the baseload condition at 2.0 bara, but the NOx levels had increased from the same conditions with configuration 4.2 (i.e. 3.2a). This would suggest that the fuel air mixing isn't optimised as a result of a reduced residence time in the CBO to mix. An image of the flame can be seen in Figure 52, note the narrower flame angle than the case of the standard CBO.

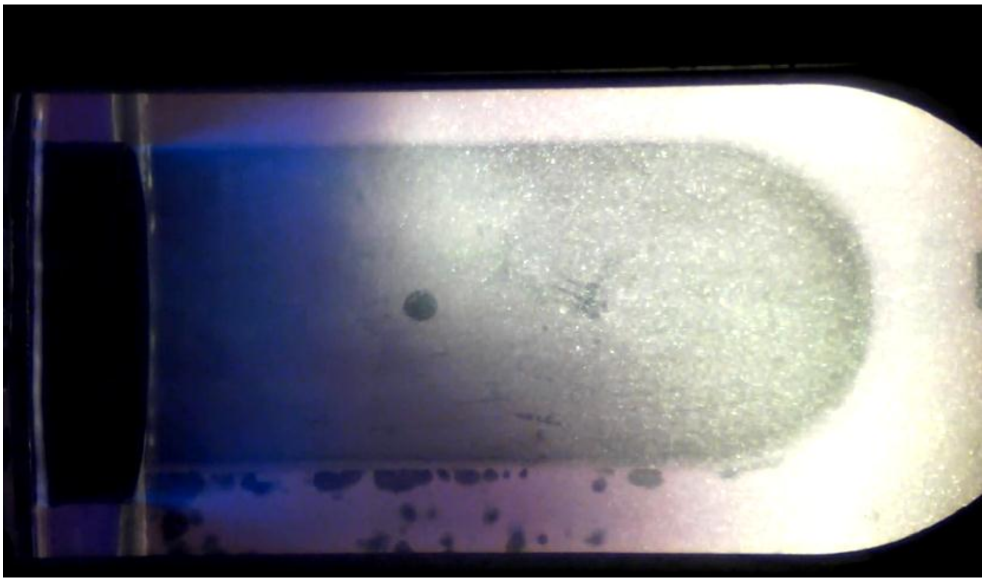


Figure 52: 2.0 bara baseload stable flame with Configuration 4.2

5th June 2013 - Syngas Burner Configuration 4.2. Syngas 2. 3.0 bara

Ansaldo provided the test conditions to be investigated which can be seen in Table 11 and Figure 53.

Table 11: 3.0 bara target engine operation conditions. Configuration 4.2

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	Pressure (Bara)	Temp (K)	MrootT/P
Base Load	1	400	964	41.6	23.1731	0.426788	2.343082	1.000	3.0	673	8.34
	2	400	964	44.5	21.6629	0.45654	2.190386	1.000	3.0	673	8.34
	3	400	964	47.8	20.1674	0.490396	2.039167	1.000	3.0	673	8.34
70% Base Load	4	365	989	40.8	24.2402	0.408	2.45098	1.026	3.0	638	8.33
	5	365	989	43.5	22.7356	0.435	2.298851	1.026	3.0	638	8.33
	6	365	989	46.5	21.2688	0.465	2.150538	1.026	3.0	638	8.33
MT	7	330	1023	38.7	26.4341	0.374138	2.672812	1.061	3.0	603	8.37
	8	330	1023	41.0	24.9512	0.396373	2.522874	1.061	3.0	603	8.37
	9	330	1023	43.6	23.4633	0.421509	2.372427	1.061	3.0	603	8.37

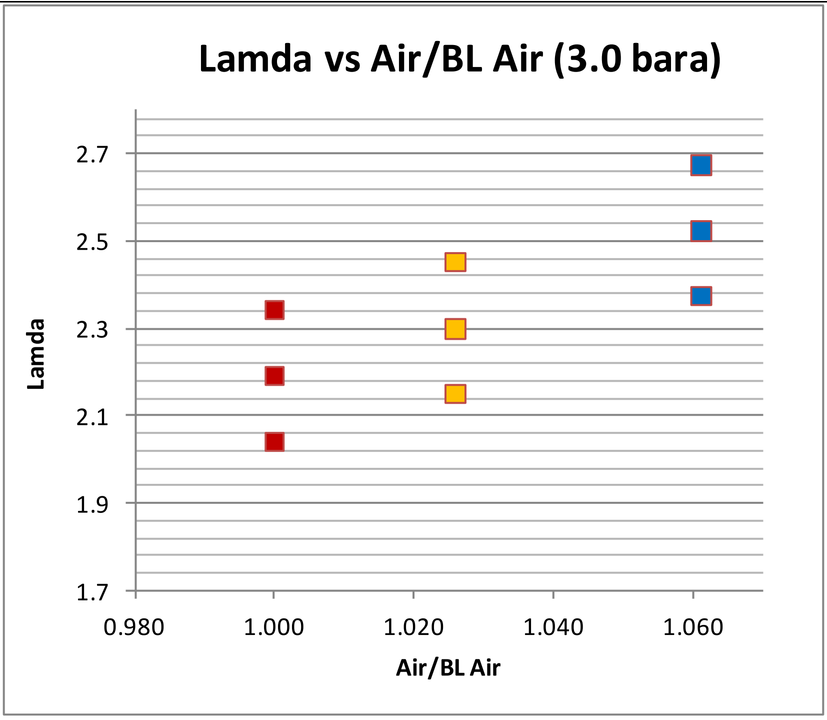


Figure 53: 3.0 bara target engine operation conditions

The experimental conditions can be seen in Figure 42. The circled areas show the test points met for each of the conditions approaching base load, 70% base load and minimum turndown; the steady periods are thus during the test points themselves. The gas analysis data can be seen in Figure 55.

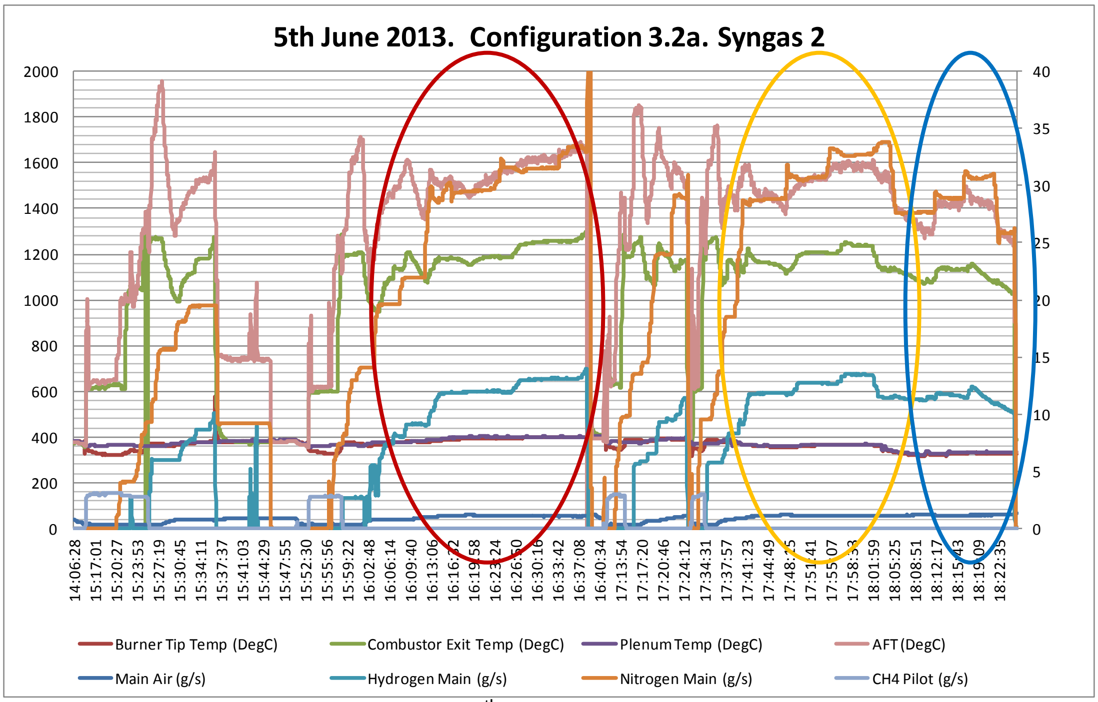


Figure 54: 5th June Rig Conditions

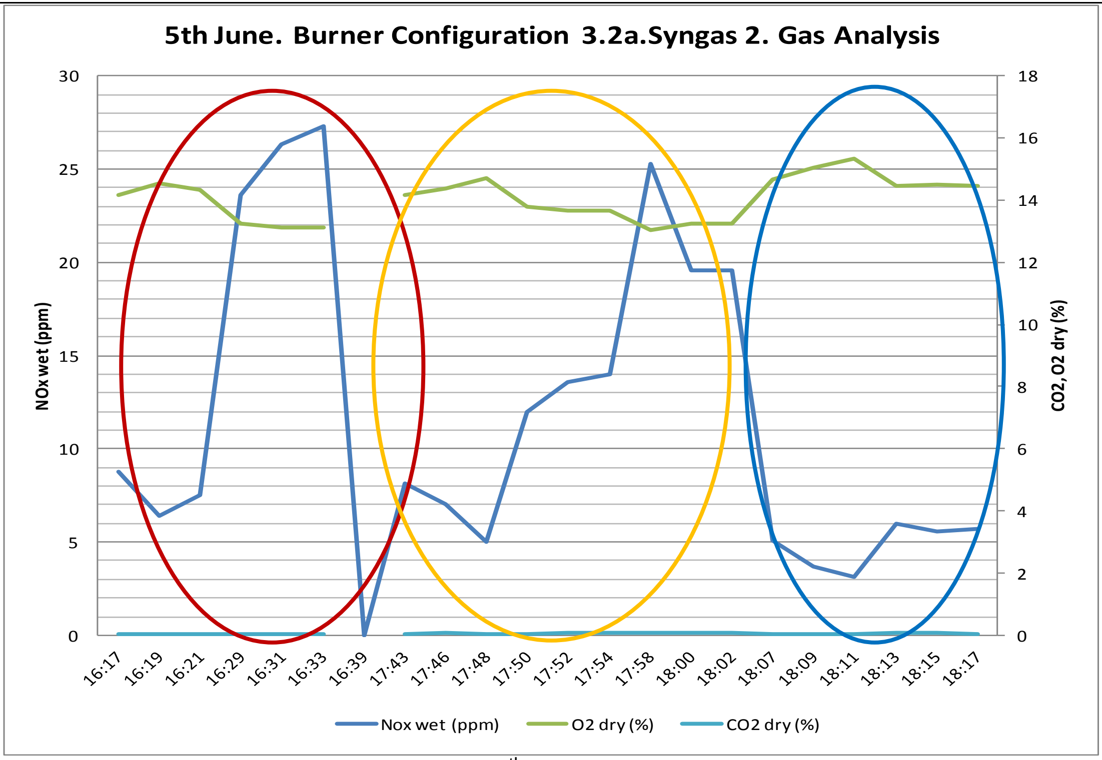


Figure 55: 29th May Gas Analysis

The experimental test points and associated burner conditions are illustrated in Table 12 and Figure 56 & 57.

Table 12: 3.0 bara actual experimental conditions

	Test Point	Temp C	Air flow local (g/s)	SG flow (g/s)	AFR	EQ Ratio	Lamda	Air/Base load Air flow	AFT C	Nox ppmV wet	Pressure (Bara)	Temp (K)	MrootT/P
Base Load	1	397	980	41.6	23.55769231	0.41982041	2.38197091	1.017	1497	7.5	3.07	670	8.26
	2	401	940	44.5	21.12359551	0.46819681	2.13585394	0.975	1625	23.6	3.04	674	8.03
	FLASHBACK	400	940	47.3	19.87315011	0.49765638	2.00941862	0.975			3.04	673	8.02
70% Base Load	4	362	980	40.5	24.19753086	0.40871939	2.44666642	1.017	1464	7.8	3.03	635	8.15
	5	365	980	43.4	22.58064516	0.43798571	2.28317949	1.017	1510	13.0	3.11	638	7.96
	6	367	980	46.5	21.07526882	0.46927041	2.13096752	1.017	1567	19.6	3.01	636	8.21
MT	7	330	1030	38.7	26.61498708	0.37159515	2.69110082	1.068	1368	4.0	3.04	603	8.32
	8	332	1010	41.0	24.63414634	0.40147525	2.49081358	1.048	1414	5.6	3.04	605	8.17
	9	Ran out of Fuel											

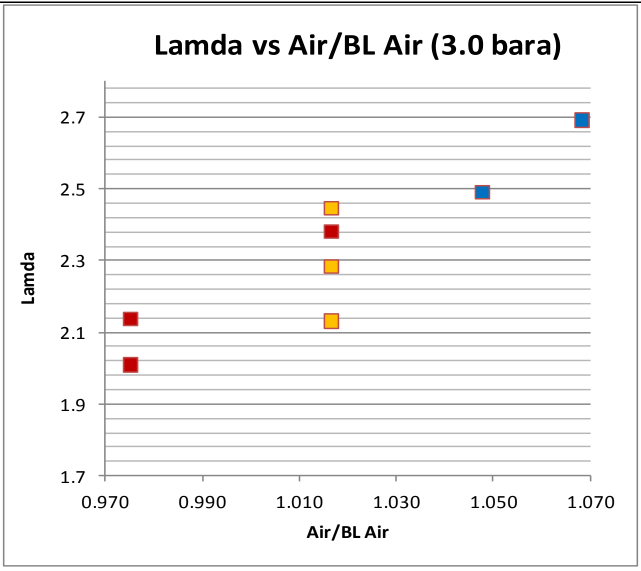


Figure 56: 3.0 bara actual experimental conditions

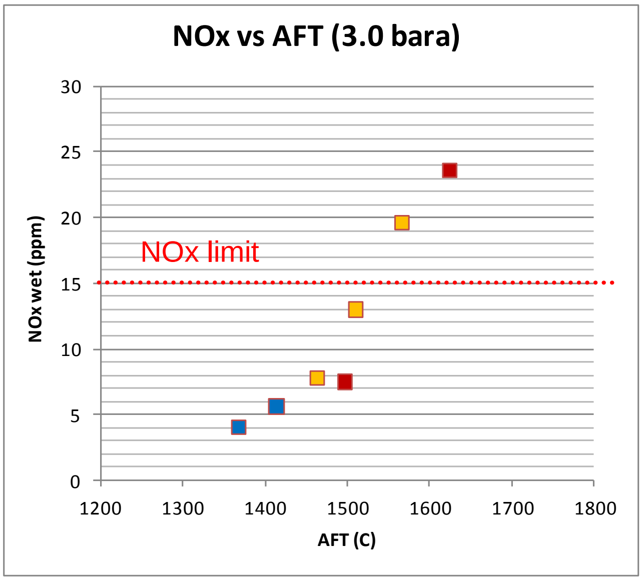


Figure 57: NOx vs AFT (calculated) at 3.0 bara.

Understandably, fuel consumption during this test was very high, and hence testing time was limited, given the finite hydrogen storage capacity. With this it was not possible to achieve the baseload condition at 3.0 bara and the NOx levels increasing slightly for comparable test points at 2.0 bara. An image of the flame approaching the base load condition (test point 2) can be seen in Figure 58. Operation of this configuration with syngas was comparatively straightforward and stable, based on operator's experience of the other tests made during the project.

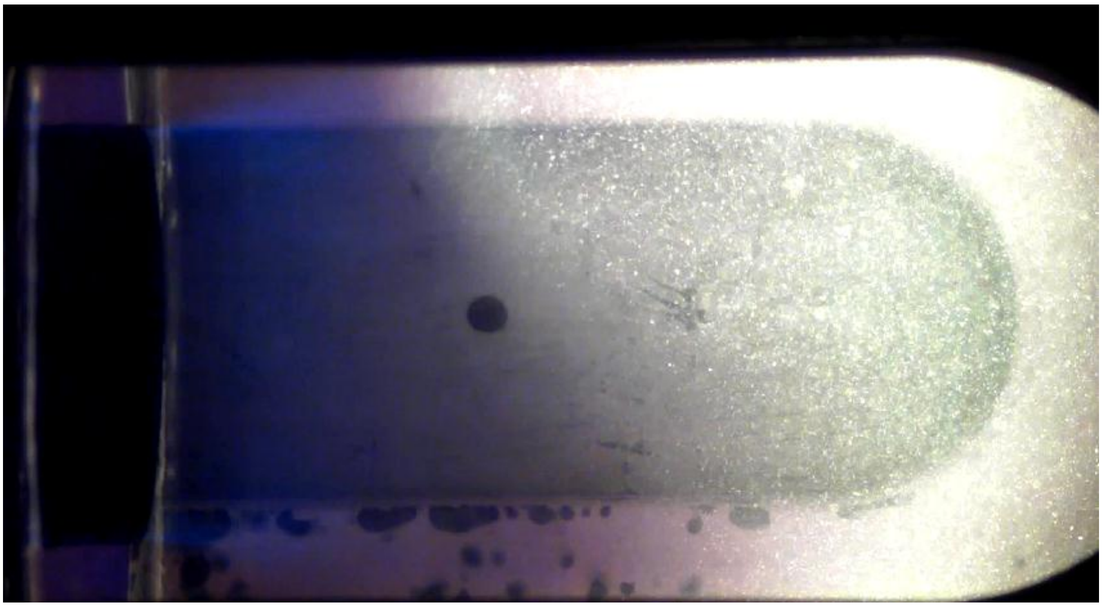


Figure 58: 3.0 bara baseload (Test Point 2) stable flame. Configuration 4.2

The NOx and AFT data that has been taken during this schedule of work has been summarised in Figure 59.

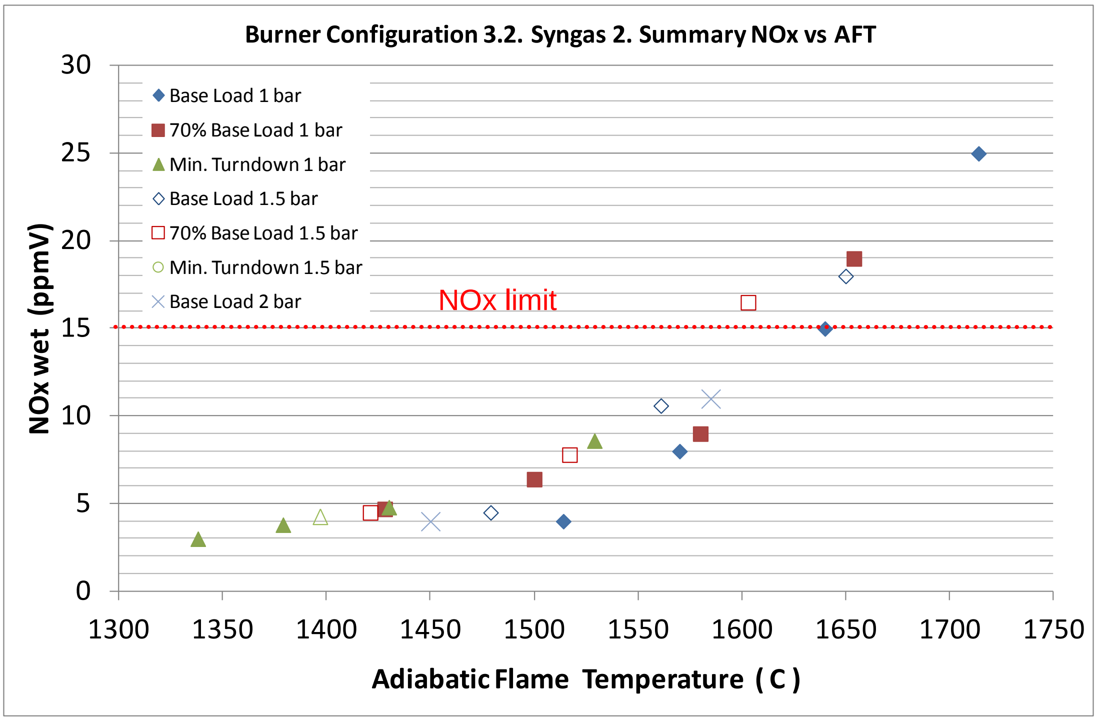


Figure 59: NOx vs AFT

The data shows that there is a reasonably consistent trend in the relationship between AFT and NOx, hence predictions of NOx in future tests can be reasonably estimated, which will allow for experimental test planning. It is advised that calculated AFT values are available to test operators in order to define potential limits of investigation.

Conclusions and Further Work

It is clear that the introduction of syngas fuel from the swirl vanes has had a positive effect on the burner performance, which is likely due to the improved air/fuel mixing. Improved mixing will ensure that there are fewer localised fuel rich pockets which results in lower NO_x formation and more homogeneous heat release. The latter having a positive impact on combustion instabilities.

The data so far is showing that increasing pressure is having an effect on the chemical kinetics of hydrogen combustion and thus providing a higher burning velocity, the flame is therefore able to burn closer to the burner exit and the risk of flashback increases. Quantifying this is difficult from the experimental data alone, but additional findings from the modelling work packages and CFD could give a better understanding and the opportunity to predict what will happen at higher pressures than those tested herein.

There is a limitation to how far the area of the burner CBO can be reduced, NOx increases and the risk of blow off for natural gas increases with reducing area. So possibly the RDA 25 is the best compromise, based on the conditions tested at GTRC. This however introduces greater potential for blow-off during operation with methane. If the final burner design must be fuel flexible then design limitations are apparent at this stage.

Unfortunately, during this phase of testing there were a significant number of occasions where flashback was not predicted. On these occasions, there did not seem to be any early indicators of flashback such as increasing burner tip temperatures or acoustic synchronisation, i.e. at the higher pressures the potential for flashback prediction was severely reduced. Also, it was not clear as to the mode of the flashback e.g. boundary layer or sheer layer.

With regard to the methane pilot, the main reason for switching the pilot off at the 1.0 bara condition was that the burner exit temperatures were exceeding the rig operating range of the exit thermocouple (1300C), hence these unusually high temperatures were a safety concern. The Enel Sesta rig may be used to running higher burner exit temperatures due to the rig design and refactory lining. In which case the Sesta rig operators may not experience any issues leaving the pilot running, other than higher NOx.

The hydrogen flame resisted blow off very well so it may be possible to operate the minimum turndown of the engine to achieve stable combustion at higher pressures. It may be possible to calculate the turbulent burning rate using the most accurate kinetic model for Hydrogen/Nitrogen mixtures for the 3.0 bara 75% base load case, which could be used as a stable threshold value during operation. This may provide a method to calculate how much the hydrogen concentration needs to be reduced for stable operation at higher pressures. Another option would be to operate with 75% Hydrogen and perhaps 10% CO2 and 15% N2 as a diluent. If the flame doesn't blow off at the lower pressures and minimum turndown, it should be able to achieve significantly higher pressures with this mixture.

Further work has been suggested by Ansaldo to test another diagonal swirler configuration with 9 holes per swirl vane instead of 10 which is representative of the larger AE94.3a burner which will be used for the full scale tests at Sesta.

APPENDIX I

Test Controller Log

Test number ETN_36_1														
19/04/2013	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Burner design	Config 3.2	Config 3.2	Config 3.2	Config 3.2	Config 3.2	Config 3.2	Config 3.2	Config 3.2	Config 3.2	Config 3.2	Config 3.2	Config 3.2	Config 3.2	Config 3.2
Fuel	CH4	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	SYNGAS 2	SYNGAS 2	SYNGAS 2	SYNGAS 2	SYNGAS 2
Design power (MW)	0	0.15	0.14	0.63	0.5	0.51	0	0	0.5	0.45	0	0	0	0.5
Air: Live Baro (mbar)	1034	1034	1034	1034	1034	1034			1034	1034	1034	1034	1034	1034
P (barG)	1.85	0.06	0.06	0.08	0.07	0.07			0.07	0.07	0.07	0.07	0.07	0.07
T ©	401	355	393	395	401	397			398	399	399	399	399	406
Dilution and cooling (kg/s)														
m air (kg/s)	0.86	0.35	0.36	0.35	0.35	0.34			0.35	0.35	0.35	0.35	0.35	0.35
Fuel (g/s) :														
Pilot	0	3	2.7	2.6	0	0			0	0	0	0	0	0
Pre-mixed	0	0	0	12.3	12.3	12.4			12.3	10.9				12.1
Ratio Pilot/Main				21.14	0	0			0	0	#DIV/0!	#DIV/0!	#DIV/0!	0
CO2 (g/s)														
Hours (on condition)														
Comments	On condition, ready to light	Lit very well.	Going to main h2 and n2	Pilot cut. I like this burner, its very stable	very stable	OK	Power loss to PLCs. Very strange	cuased a flashback when re-lighting the premix. Try again.	Back on condition, ready to try some lower power settings for AFTs	AFT = 1330	AFT = 1380	AFT = 1510	AFT = 1600	Back to 500kW nominal, ready for He
Comments						Will tweak the H2 down a bit	Fault occurred twice. Looks like an electrical issue.							
Fuel CV (MJ/kg)	41	41	41	41	41	41	41	41	41	41	41	41	41	41
AFR stoich by mass		9.89	9.89	9.89	9.89	9.89			9.89	9.89	9.89	9.89	9.89	9.89
Global ϕ at design condition		0.08	0.07	0.42	0.35	0.36			0.35	0.31				0.34
Global Volumetric concentration														
Pilot Volumetric concentration %														
Sanity check on equivalence ratio														
Time	14:00	14:20	14:38	14:46	15:01	15:15	15:40	16:05	16:25	16:32	16:36	16:40	16:45	16:49

Test number ETN_37_1														
23/04/2013	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Burner design	Config 3.3	Config 3.3	Config 3.3	Config 3.3	Config 3.3	Config 3.3	Config 3.3	Config 3.3	Config 3.3	Config 3.3	Config 3.3	Config 3.3	Config 3.3	Config 3.3
Fuel	CH4	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	CH4/SYNGAS 2	SYNGAS 2	SYNGAS 2	SYNGAS 2	SYNGAS 2	SYNGAS 2
Design power (MW)														
Air: Live Baro (mbar)	1030													
P (barG)			0.07	0.06		0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	
T ©			382	388		409	399	397	398	398	399	399	399	
Dilution and cooling (kg/s)														
m air (kg/s)	170	350	340	360		350	350	350	350	350	350	350	350	
Fuel (g/s) :														
Pilot	2.3	2.8	0	2.9		0	0	0	0	0	0	0	0	
Pre-mixed		1.6	12.2			12.2	12.2	12.2	12.2	12.5	13.2	13.7	14.5	
Ratio Pilot/Main					0	0			0	0	#DIV/0!	#DIV/0!	#DIV/0!	0
CO2 (g/s)														
Hours (on condition)														
Comments														
Comments														
Fuel CV (MJ/kg)														
AFR stoich by mass		9.89	9.89	9.89	9.89	9.89			9.89	9.89	9.89	9.89	9.89	9.89
Global ϕ at design condition		0.08	0.07	0.42	0.35	0.36			0.35	0.31	0.31			0.34
Global Volumetric concentration														
Pilot Volumetric concentration %														
Sanity check on equivalence ratio														
Time	15:10	15:30	15:42	16:00	16:40	16:44	16:55	17:25	17:30	17:38	17:46	17:50	17:53	17:56
	First light up at 140 g/s did not work.	SG came on OK	Pilot cut.	Re-lit OK	Re-lit OK	On condition now. Nice and stable	This burner seem to flicker more. Might be precessing?	OK, getting through fuel quite quick though.			OK, Still working GA fully working			Didn't log the data, I was outside.
	OK lit at 170 g/s		Sounds a bit 'whiney'	Lost control over SG line 3.										
			Blow-off 3 minutes after test point. Not due to burner!	Loose pipe on board, fixed after 30 minutes.										
		Gas analysis problems.				Yura and Angharad still working the GA problem				upped the fuel for another AFT	AFT = 1510	AFT = 1545	AFT = 1580	AFT = 1620

Test number ETN_38_1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1
25/04/2013	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Burner design	Config 3.2																				
Fuel	CH4	CH4	CH4	CH4	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2
Design power (MW)																					
Air: Live Baro (mbar)	1029	1029	1029	1029	1029	1029	1029	1029	1029	1029	1029	1029	1029	1029							
P (barG)		1.93	0.05	0.05	0.07	0.07	0.08	0.08	0.08	0.08	0.09	0.08	0.08	0.08	0.03	0.03	0.05	0.05	0.06	0.15	0.16
T ©		398	385	401	399	399	405	393	362	365	365	327	329	328	341	341	323	323	284	282	270
Dilution and cooling (kg/s)																					
m air (kg/s)		0.55	0.34	0.36	0.36	0.36	0.36	0.36	0.37	0.37	0.38	0.39	0.39	0.39	0.18	0.28	0.4	0.4	0.5	0.8	0.9
Fuel (g/s) :																					
Pilot		0	2.6	2.9	0	0	0	0	0	0	0	0	0		0.89	0.89	0.74	0.74		0.39	0.8
Pre-mixed		0	0		10.2	12.2	15.2	16.6	13.7	15.6	17.5	12.2	14.6	16.7							
Ratio Pilot/Main	0	0	0	0	0	0	0	0	0	0	0	0	0	0							
CO2 (g/s)																					
Hours (on condition)																					
Comments		About to light u	Light up now	aiting for equ	Pilot cut	Main up		Rig getting too h	e rig overheating and high Nox		Flame is flickering a bit				Tried to light on SG. Instant FB and burner glowed after 5 secs!	Tried to light on SG. Instant FB and burner glowed after 5 secs!	Tried to light on SG. Instant FB and burner glowed after 5 secs!	Tried to light on SG. Instant FB and burner glowed after 5 secs!		Nope	
Comments	ved with airflows to practic		Lit well		Ultra lean	nditions set as 19th April										Higher airflow this time		Also ran the N2 purge!			
Fuel CV (MJ/kg)					41	41	41	41	41	41	41	41	41	41							
AFR stoich by mass	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89							
Global ϕ at design condition	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08							
Global Volumetric concentration																					
Pilot Volumetric concentration %																					
Sanity check on equivalence ratio																					
Time		11:05	11:37	11:40	11:50	11:56	12:05	12:14	12:24	12:29	12:34	12:40	12:45	12:50	12:54	14:06					
Test Point Number					0	0a	1	2	4	5	6	7	8	9							
	Emissions and temperatures do not match very well with the test conducted on 19/04/13. Main difference is that we used premixed fuel packs in this test.																				

Test number ETN_39_1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1				
01/05/2013	1	1	1	1	1	1	1	1	1	1	1	1	1	1				
Burner design	Config 3.2																	
Fuel	CH4	CH4	CH4	CH4	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2				
Design power (MW)																		
Air: Live Baro (mbar)	1029																	
P (barG)	0.04		0.07	0.07	0.07	0.08	0.08	0.07	0.07	0.08	0.07	0.07	0.07	0.08	0.08	0.54		
T ©	384		397	403	396	400	401	364	363	363	364	330	325	326	329	362		
Dilution and cooling (kg/s)																		
m air (kg/s)	330	370	370	370	380	370	370	380	380	370	370	390	390	390	400	560		
Fuel (g/s) :																		
Pilot		2.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Pre-mixed			12.2	14	15	16.1	17.4	13.8	14.7	15.7	16.9	13.1	13.9	14.8	15.8	22		
Ratio Pilot/Main	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
CO2 (g/s)																		
Hours (on condition)																		
Comments	About to light	Pilot cut	ndition. Look	Good.	Good	emp getting	higher, but n	he fuel a bit d	opped after 3	OK.	own a little after 4 minutes					Shut down to re-light and pressurise.	Got about 5 minutes on condition. Worked well.	
Comments	rove up to condition 0.					Stayed for only 5 mins to save fuel.										Dilution fan 2 not responding. Checked calculations . Happy to run at 6.3 g/s H2 with 1 fan.	End. Ran out of H2.	
Fuel CV (MJ/kg)					41	41	41	41	41	41	41	41	41	41				
AFR stoich by mass	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89				
Global ϕ at design condition	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08				
Global Volumetric concentration																		
Pilot Volumetric concentration %																		
Sanity check on equivalence ratio																		
Time	16:56	17:15	17:18	17:25	17:37	17:49	18:00	18:09	18:21	18:34	18:46	19:01	19:14	19:26	19:37	20:45	20:50	
Test Point Number			0A	1	2	3	4	5	6	7	8	9	10	11	12	13		

Test number ETN_40_1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1
02/05/2013	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Burner design	Config 3.2																				
Fuel	CH4	CH4	CH4	CH4	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2
Design power (MW)																					
Air: Live Baro (mbar)	1028																				
P (barG)				0.58				0.69	0.53	0.51	0.56	0.51	0.54	0.52							
T ©				394				401	401	362	361	364	364	332							
Dilution and cooling (kg/s)																					
m air (kg/s)										560	580	540	540	560							
Fuel (g/s) :																					
Pilot				0				0	0	0	0		0	0							
Pre-mixed				20.8				23.9	23.9	20.4	21.8		23.3	20.5							
Ratio Pilot/Main	0	0	0	0	0	0	0	0	0	0	0	0	0	0							
CO2 (g/s)																					
Hours (on condition)																					
Comments	About to light	PLC Power out	Restarted OK	Quite stable.	Flashback. I brought the H2 up a bit fast.		Couple of air fluctuations here. Stayed a bit longer at TP.	A bit lean	Backed off the air			Tweeked air down a bit from TP 5			PLC power loss again.	Re-lit for 2 bar run	Flame sat too close to burner tip.	Re-lit OK	Now trying to light and drive with back pressure valve open.	Got up to almost 8.0 g/s H2	PLC power outage
Comments	Lit well. Drove up to condition 0.					Couple of flameouts when driving back up.									Kept the TP		As we ran up through pressure, the flame sat closer to the burner	Now we got blow off.		Then ran out of fuel!	End.
Fuel CV (MJ/kg)					41	41	41	41	41	41	41	41	41	41							
AFR stoich by mass	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89							
Global ϕ at design condition	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08							
Global Volumetric concentration																					
Pilot Volumetric concentration %																					
Sanity check on equivalence ratio																					
Time	14:50	15:09	15:11	15:21	15:31		16:06	16:19	16:25	16:34	16:43	16:48	16:55	17:06	17:10	18:49	19:20	19:30	19:35		20:35
Test Point Number				1			2	3	3A	4	5	5A	6	7							

Test number ETN_41	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1	Config 4.1
29/05/2013	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Burner design	Config 3.2																	
Fuel	CH4		SG2															
Design power (MW)																		
Air: Live Baro (mbar)	1014																	
P (barG)	1.11		0.06	0.51	1.08	1.1	1.02	1.01	1.07	1.08	1.11	1.1						
T ©	406		388	399	399	400	365	364	363	327	330	331						
Dilution and cooling (kg/s)																		
m air (kg/s)	730		350	530	730	740	740	730	750	760	760	760						
Fuel (g/s) :																		
Pilot	0		0	0	0	0	0	0	0	0	0	0						
Pre-mixed	0		12.3	20.9	27.6	29.7	27.2	29	31	25.8	27.3	29						
Ratio Pilot/Main	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
CO2 (g/s)																		
Hours (on condition)																		
Comments	About to light	Lit OK at 2 g/s pilot	Stable at 500kW	Stable at 750kW		FB							FB					
Comments																		
Fuel CV (MJ/kg)					41	41	41	41	41	41	41	41	41	41				
AFR stoich by mass	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89				
Global ϕ at design condition	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08				
Global Volumetric concentration																		
Pilot Volumetric concentration %																		
Sanity check on equivalence ratio																		
Time	13:42	13:52	14:10	14:27	15:00	15:06	15:31	15:38	15:48	15:58	16:04	16:10						
Test Point Number			0A	0B	1	2	4	5	6	7	8	9	2 (RPT)					
																5	3.6	8.6
																9.9	11.1	21
																		29.6

Test number ETN_42	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2
30/05/2013	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Burner design	Config 3.2													
Fuel	CH4		SG2											
Design power (MW)														
Air: Live Baro (mbar)	1017													
P (barG)	1.23													
T ©	405													
Dilution and cooling (kg/s)														
m air (kg/s)	760													
Fuel (g/s) :														
Pilot	0													
Pre-mixed	0													
Ratio Pilot/Main														
CO2 (g/s)														
Hours (on condition)														
Comments	About to light	Lit fine												
Comments														
Fuel CV (MJ/kg)					41	41	41	41	41	41	41	41	41	41
AFR stoich by mass	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89
Global ϕ at design condition	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Global Volumetric concentration														
Pilot Volumetric concentration %														
Sanity check on equivalence ratio														
Time	14:36	14:42												
Test Point Number														

Test number ETN_43	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2
05/06/2013	1	1	1	1	1	1	1	1	1	1	1	2	3	1
Burner design	Config 3.2													
Fuel	CH4		SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2
Design power (MW)														
Air: Live Baro (mbar)	1024													
P (barG)	0.71	0.05			0.05	1.2	1.3	1.58	2.01	2	2.03	2.04	2.03	
T ©	383	389			391	536	584	608	568	603	604	624	625	
Dilution and cooling (kg/s)														
m air (kg/s)	700	370			360	760	730	800	1001	1080	1100	1040	1070	
Fuel (g/s) :														
Pilot	0	3			0	0	0	0	0	0	0	0	0	
Pre-mixed	0				20	25	27.7	31	31	41.6	~43	44.5	46.8	
Ratio Pilot/Main														
CO2 (g/s)														
Hours (on condition)														
Comments	About to light	Lit fine	Bringin up the air	FB and fuel problem. Fixed.	Stable flame. Blue region close to burner.	Stable flame. Small visible region close to nozzle.	Stable flame. Very small visible region close to nozzle.	Stable flame. Extremely small visible region.	Stable flame. Small visible region close to nozzle.	Stable flame. Extremly small visible region.	Increasing N2. Flame has almost disappeared.	Stable flame (increased H2). Flame almost disappeared.	Flashback.	
Comments														
Fuel CV (MJ/kg)					41	41	41	41	41	41	41	41	41	41
AFR stoich by mass	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89
Global ϕ at design condition	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Global Volumetric concentration														
Pilot Volumetric concentration %														
Sanity check on equivalence ratio														
Time	15:12	15:16		15:45	16:01	16:05	16:07	16:09	16:11	16:14	16:17	16:23	16:38	
Test Point Number														

Test number ETN_43	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2
05/06/2013	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.2	2.3			
Burner design	Config 3.2													
Fuel	CH4	SG2 & CH4	SG2 & CH4	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2			
Design power (MW)														
Air: Live Baro (mbar)	1024													
P (barG)	0.02	0.05	0.05	0.05	0.6	0.69	1.69	1.82	2.07	2.12	2.1			
T ©	407	410	409	564	590	567	612	613	602	565	597			
Dilution and cooling (kg/s)														
m air (kg/s)	180	360	360	360	500	660	740	810	1110	1200	1090			
Fuel (g/s) :														
Pilot	2.7	3	2.9	0	0	0	0	0	0	0	0			
Pre-mixed	0	3	10	19	21	31	31	33	40.8	43.4	46.5			
Ratio Pilot/Main														
CO2 (g/s)														
Hours (on condition)														
Comments	Lit fine	Flame alright	Dirty flame (yellow)	Stable Flame. Long visible region.	Stable flame. Small visible region.	Stable flame. Small visible region close to nozzle.	Stable flame. Small visible region.	Stable flame. Small visible region.	Stable flame. Very small visible region.	Stable flame. Small visible region.	Stable flame. Small visible region. Chamber purple.			
Comments														
Fuel CV (MJ/kg)					41	41	41	41	41	41	41	41	41	41
AFR stoich by mass	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89
Global ϕ at design condition	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Global Volumetric concentration														
Pilot Volumetric concentration %														
Sanity check on equivalence ratio														
Time	17:12	17:13	17:14	17:15	17:17	17:18	17:20	17:21	17:42	17:52	17:57			
Test Point Number														

Test number ETN_43	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2	Config 4.2
05/06/2013	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.2	3.3			
Burner design	Config 3.2													
Fuel	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2	SG2			
Design power (MW)														
Air: Live Baro (mbar)	1024													
P (barG)	1.89	2.11	2.01	2.04	2.07	2.09								
T ©	573	539	561	560	532	515								
Dilution and cooling (kg/s)														
m air (kg/s)	1140	1200	1110	11120	1180	1220								
Fuel (g/s) :														
Pilot	0	0	0	0	0	0								
Pre-mixed	38.7	41	41	42.4	38	34								
Ratio Pilot/Main														
CO2 (g/s)														
Hours (on condition)														
Comments	Stable flame. Visible region attached to nozzle.	Stable flame. Visible region attached to nozzle.	Stable flame. Visible region attached to nozzle.	Stable flame. Visible flame attached to nozzle.	Stable flame. Visible flame attached to nozzle.	Stable flame. Visible flame attached to nozzle.								
Comments														
Fuel CV (MJ/kg)	41	41	41	41	41	41	41	41	41	41	41	41	41	41
AFR stoich by mass	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89	9.89
Global ϕ at design condition	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Global Volumetric concentration														
Pilot Volumetric concentration %														
Sanity check on equivalence ratio														
Time	18:06	18:12	18:15	18:20	18:23	18:26								
Test Point Number														

APPENDIX II
Burner Configurations

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
GTRC GAS TURBINE RESEARCH CENTRE
www.cu-gtrc.co.uk

H2-IGCC BURNER CONFIGURATIONS

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H_2IGCC Energy without CO_2

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
GTRC GAS TURBINE RESEARCH CENTRE
www.cu-gtrc.co.uk

Standard natural gas burner. AE64.3a. Installation 20 May 2011

- Small diameter holes for CH4 pre-mix in diagonal swirler vanes
- Individual pilot and diffusion CH4 holes located radially around the central burner which caused some confusion over which to use.
- Short ignitor giving ignition problems

Syngas Burner Configuration 1. Installation
15 March 2012

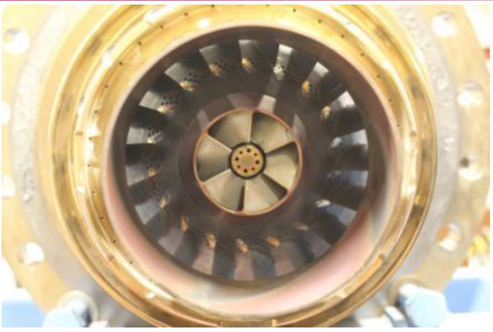
www.cu-gtrc.co.uk

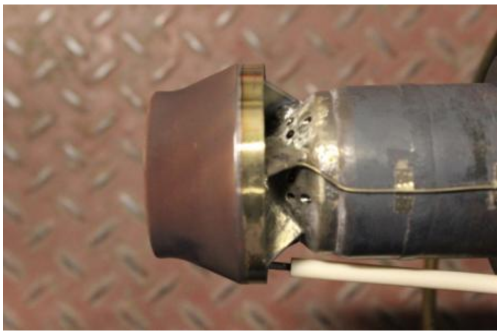
• Diagonal Swirler S0839. Syngas premix main consists of rectangular grouping of 7x2mm holes between each swirl vane. 18 sets in total.

• Diagonal swirler SO839. Methane premix main consists of a line of 5x1mm diameter holes in each of the 18 guide vanes

Syngas Burner Configuration 1. Installation
15 March 2012

www.cu-gtrc.co.uk





• 6xCH4 pilot holes located radially around the central burner.

•12xSyngas pilot holes located just below the CH4 pilot holes

• Longer ignitor solves ignition problems

• RDA0 with Standard CBO

Syngas Burner Configuration 2.1.
Installation 01 October 2012

www.cu-gtrc.co.uk

- Diagonal Swirler S0838. Syngas premix main consists of 18x5.2mm diameter holes located radially between each swirl vane.
- Diagonal swirler SO838. Alternative Premix main consists of a line of 5x2.6mm diameter holes in each of the 18 guide vanes

Syngas Burner Configuration 2.1.
Installation 01 October 2012

www.cu-gtrc.co.uk

- 6xCH4 pilot holes located radially around the central burner.
- 12xSyngas pilot holes located just below the CH4 pilot holes
- Longer ignitor solves ignition problems
- RDA25 with CBO

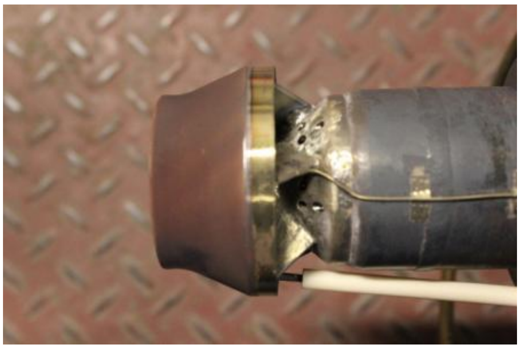
Syngas Burner Configuration 2.2.
Installation 03 October 2012

www.cu-gtrc.co.uk

- Diagonal Swirler S0840. Syngas premix main consists of circular groupings of 12x2mm diameter holes located radially between each swirl vane.
- Diagonal swirler S08340. Alternative premix main consists of a line of 5x2.2mm diameter holes in each of the 18 guide vanes

Syngas Burner Configuration 2.2.
Installation 03October 2012

www.cu-gtrc.co.uk



- 6xCH4 pilot holes located radially around the central burner.
- 12xSyngas pilot holes located just below the CH4 pilot holes
- Longer ignitor solves ignition problems
- RDA0 without CBO

Syngas Burner Configurations Overview

www.cu-gtrc.co.uk

Syngas Burner Configuration 3.1. Installation 26 November 2012

www.cu-gtrc.co.uk

- Diagonal swirler SO838. Syngas premix main consists of a line of 5x2.6mm diameter holes in each of the 18 guide vanes
- 6xCH4 pilot holes located radially around the central burner.
- 12xSyngas pilot holes located just below the CH4 pilot holes
- RDA0 with CBO

Syngas Burner Configuration 3.2.
Installation 28 November 2012

www.cu-gtrc.co.uk

- Diagonal swirler SO839. Syngas premix main consists of a line of 5x1mm diameter holes in each of the 18 guide vanes
- 6xCH4 pilot holes located radially around the central burner.
- 12xSyngas pilot holes located just below the CH4 pilot holes
- RDA0 with CBO

Syngas Burner Configuration 3.3.
Installation 03 December 2012

www.cu-gtrc.co.uk

- Diagonal swirler SO840. Syngas premix main consists of a line of 5x2.2mm diameter holes in each of the 18 guide vanes
- 6xCH4 pilot holes located radially around the central burner.
- 12xSyngas pilot holes located just below the CH4 pilot holes
- RDA0 with CBO

Syngas Burner Configuration 4.1.
Installation May 2013

www.cu-gtrc.co.uk

- Diagonal swirler SO839. Syngas premix main consists of a line of 5x1mm diameter holes in each of the 18 guide vanes
- 6xCH4 pilot holes located radially around the central burner.
- 12xSyngas pilot holes located just below the CH4 pilot holes
- RDA0 with CBO

Syngas Burner Configurations

www.cu-gtrc.co.uk


Config 1.0


Config 2.1


Config 2.2


Config 3.1

Syngas Burner Configurations

www.cu-gtrc.co.uk

Config 3.2 | Config 3.3 | Config 4.1 (3.2) | Config 4.2 (3.2a)