BIPO – DEVELOPMENT ENGINES

Test No.	BE-GEN-002	Engine Variant	GEN1	Issue level & Date	Issue 01 14 Sept. 2021

1 TEST AIM

This BIPO (Break-In and Pass-Off) or 'running-in' test procedure has been developed to control the first operation of newly built or rebuilt prototype engines, in order to ensure that they are suitably pre-conditioned and performing correctly before these engines are then used for further test work.

This procedure is only applicable for test engines that will be used for calibration, durability, or functional testing work. **This procedure does not cover a BIPO sequence for production engines.**

2 GENERAL DETAILS

The objectives of this test are to :

- Condition and break-in the engine over a controlled, repeatable process
- Confirm that the engine fulfils engine performance targets
- Ensure engine has no fluid or gas leaks.
- Confirm that no abnormal noises occur when engine is running
- Ensure that at each control point, all engine systems are operating correctly, and engine parameters stabilise within expected limits

Additionally, the BIPO should be used to verify functionality of any engine instrumentation that has been added, or conditioning rigs connected, for any follow-on functional or durability testing.

If any issues occur during the BIPO test, there is an option to correct the fault before commencing the desired test work. This is to prevent valuable test time being lost during the main test work by identifying early if an engine is functioning incorrectly.

Note: Not all engines will require a BIPO to be run as certain tests may need to assess a newly built 'green' engine as part of its functional test programme (e.g., Piston scuff tests).

3 ENGINE AND TESTBED PREPARATION / INSTALLATION

Depending on the test procedure that the BIPO engine will go on to perform, it may be required to assess certain engine wear characteristics. Details will be given in the subsequent test procedure or engineering team test instructions.

Often some of the measurements required will need to be carried out <u>during the engine build process</u> and then repeated <u>during the engine teardown process</u> post-test.

Appendix 13 contains an example list of typical engine measurements. The requesting test engineer should advise which measurements are required (in addition to the standard build measurements).

During the engine build, the full build process should be adhered to, ensuring that the following typical tasks are completed :

- Final torque values for critical fasteners are recorded in the build book
- Measure and record the vacuum achieved for intake and exhaust ports in cylinder head with valves installed
- Check engine for leakages during the build pressure test(s)
- The as-built Big-end and Main bearing clearances and crank end-float are recorded
- The final valve clearances are recorded
- Any issues found on build are noted with details of rectification or corrective actions
- Record any modifications or build deviations made during build
- Individual component serial numbers (where specified) are noted (e.g. Turbochargers, Injectors, etc.)

Ensure all parts that require adaption for instrumentation are modified, and subsequently leak-tested and cleaned prior to engine assembly.

Unless otherwise instructed the fluid specifications for this test are:

Fluid	Required Specification	Notes
Fuel	DHPP - A	EN590 or Winter-grade DHPP-A may also be specified
Lube Oil	5W50 (Mobil 1 or equiv.)	Renew Oil & filter @ 200hrs
Engine coolant	Water with inhibitors	50:50 Water/Eth. Glycol mix may also be specified

Ideally the BIPO should be conducted with the same fluid specs as the planned follow-on test. If this is not the case it is recommended that the appropriate engine and test bed system(s) are suitably flushed with the intended fluid(s) prior to the test start.

4 EQUIPMENT & INSTRUMENTATION

Refer to procedure **BE-GEN-001 – Test Cell Set Up** for details on test cell facilities and test bed control parameters.

For this test, only the standard test instrumentation (specified in **BE-GEN-001 – Test Cell Set Up)** is required to be fitted to the engine. However, additional instrumentation which has been fitted during the build for the subsequent follow-on testing should also be logged during the BIPO. This enables any instrumentations errors or issues to be rectified prior to the start of test and also provides additional data in cases of early-life engine failure.

Performance rating is to be carried out as per ISO 1585 (with appropriate accessories and accuracy).

5 ECU PARAMETER LOGGING REQUIREMENTS

Other than the Standard ECU parameters defined in **BE-GEN-001 – Test Cell Set Up** no additional ECU parameters are to be logged during this test, unless specified in the follow-on test procedure or requested by the responsible test engineer.

6 TEST SAFETY SHUTDOWN LIMITS

Refer to **BE-GEN-001 – Test Cell Set Up** for details on test cell safety shutdown limits.

7 MONITORING REQUIREMENTS

Refer to **BE-GEN-001 – Test Cell Set Up** for details of standard monitoring and reporting requirements as well as details on daily and periodic checks / service requirements.

In addition, after every cycle, the following is to be performed:

Every 2.5 hr test cycle	• Review measured parameters and check for any cycle-to-cycle anomalies or variations that may require further investigation (Cross plot the 1Hz data from each cycle for each parameter)
	• General visual inspection of engine and dyno driveline condition
	• Any evidence of any fluid or gas leaks around engine / gearbox and test cell
	    o Please photograph and log in logbook
	    o If severe inform requesting engineer
	• Check for any abnormal noises at idle condition
	• Check oil level via dipstick markings and record (check 300 seconds after shutdown from idle)
	    o Top up if required – weigh amount added and add into the testbed logbook
	    o If oil consumption is severe, inform requesting engineer
	• Check cooling system header tank levels, if top-up is necessary allow coolant to cool (<70deg.C) before releasing the pressure cap. Record any volume added

8 PRE-TEST ACTIVITIES

Prior to the test commencing, the following is to be completed (examine engine build book as some activities may have already been completed):

Measurements *(check recorded in engine build / logbook)*	• Pre-test measurement requirements for each engine to be advised during engine build process. Check that all measurements have been completed prior to starting BIPO. Consult appropriate engineer for instruction if any have been omitted
Components	• Review if there are any necessary engine rework, component replacement or updates required before commencing test. A fully jacked-open thermostat may be specified for more reliable test bed temperature control.
Checks	• Test bed cooling system fully filled, primed, and bled. Retain 100ml sample of coolant used for fill • Air path leak check • Installation for fluid and gas leaks

	• All pre-test cell calibrations have been completed (i.e. test cell calibration certificate is current) • Exhaust system connected and appropriately isolated and supported • Exhaust back pressure valve to be initially fully-open • Check all electrical harness connections are secure and correct • Check engine installation for any heat shielding requirements
Oil Requirements	• Engine is to be filled with fresh oil and fitted with new oil filter prior to start of functional test (Initial fill volume required TBC) • Sample of fresh oil (100ml) to be taken, labelled and retained • Record initial oil volume that is added to engine and all subsequent top-ups
Pre-Start	• Check fuel system is connected and primed and fuel delivery valve open • Check oil level is correct on dipstick and adjust if necessary • Rotate engine two-full revolutions by hand monitoring for any excessive friction or unusual behaviour or noises • Initiate logger at 10Hz • Static instrumentation check (e.g. reading ambient temps./pressures) • Turn ignition on and check that the lube system priming pump runs • Ensure oil pressure in main gallery exceeds 100kPa • Start engine (Crank engine for a maximum period of 20s) • Only crank engine x3 times max. ○ If required oil pressure is not achieved, or fails to start, stop and investigate
Post-initial engine start	• Coolant system pressure check at idle for leaks • Check dipstick oil level (performed after engine has idled for 300s and stopped for 600s) • Set exhaust back pressure valve (0.1kPa at rated speed condition) • Ensure no abnormal noises at idle • Check for any fluid or gas leaks at idle

Any issues found on test or post BIPO part updates please log in testbed logbook and retain and label any parts changed.

9 TEST PROCEDURE

The purpose of this test is to BIPO an engine that will be used for further test bed or vehicle-based functional or durability testing.

9.1 TEST DURATION

The cycle time is 150 minutes (2.5hrs) and in normal circumstances should be run 3 times to accrue 7.5 hours in total.

Repeating the cycle multiple times enables any relative changes between cycles as the engine beds-in or 'settles', to be assessed, and also gives an indication of expected level of variability of logged engine parameters and control conditions.

	Value	Units
Time / Test Cycle	150 / (2.5)	Mins / (hrs)
Default number of Test Cycles	3	#
Total Test Time	7.5	hrs

In some instances, such as for settling of the engine after a major rework or rectification, the requesting test engineer may specify that only one cycle is run (e.g. following a turbo or cylinder head swap).

Note: It is not recommended that a shortened break-in is used if either the piston, liner or rings have been replaced.

9.2 TEST CONTROL SETPOINTS

Test bed control set points as follows:

Parameter	Unit	Value
Coolant Outlet Temperature	°C	90
Fuel Temperature	°C	40
Air Intake Temperature	°C	25
Oil Level	Ltr	Max Fill
Engine Speed	rpm	See Test Cycle Sequence Table
Engine Load	%	See Test Cycle Sequence Table
Rated Engine Speed	rpm	2600
Rated Engine Power	kW	1103

9.3 TEST CYCLE SEQUENCE

The BIPO test cycle is defined as below:

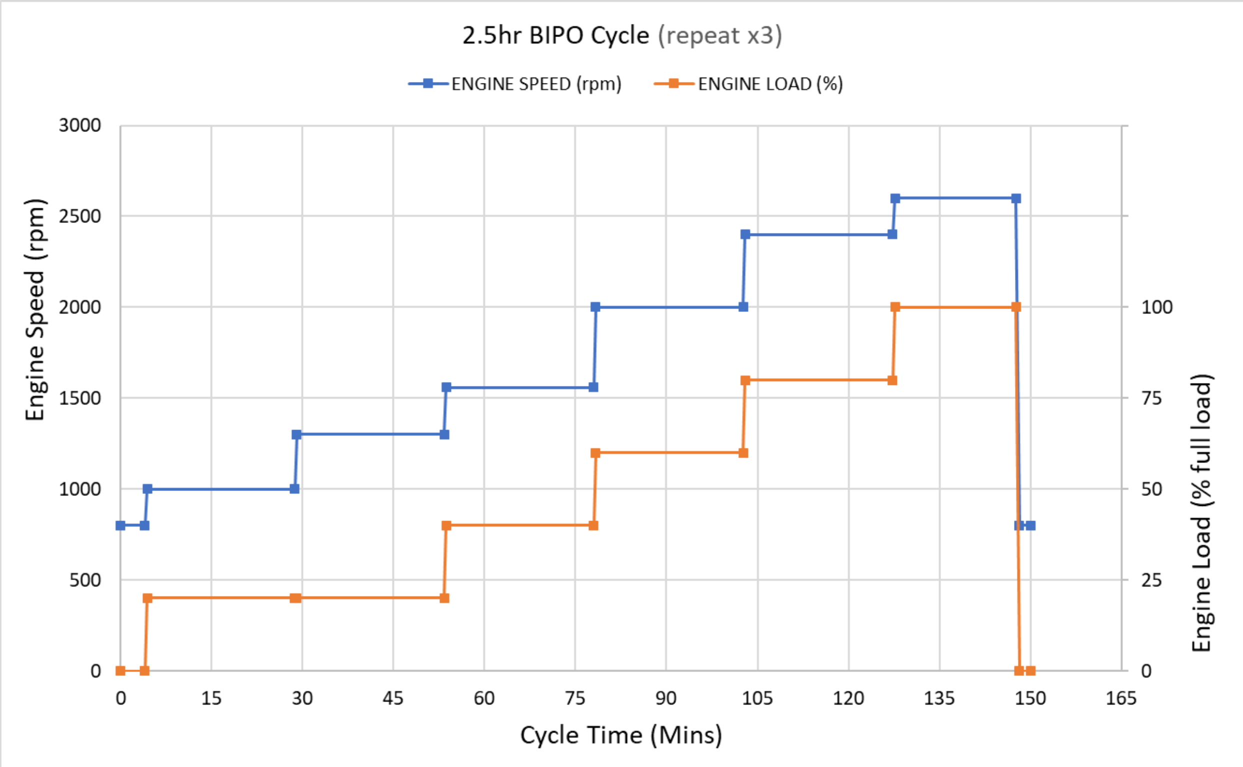
STAGE No.	STAGE TIME (s)	TOTAL TIME (mins)	ENGINE SPEED (rpm)	ENGINE LOAD (%)	DYNO TORQUE* (Nm)	DYNO POWER (kW)
1	240	4.00	idle	0	0	idle
Ramp	20	4.33	1000	20		
2	1460	28.67	1000	20	600*	59
Ramp	20	29.00	1300	20		
3	1460	53.33	1300	20	900*	122
Ramp	20	53.67	1560	40		
4	1460	78.00	1560	40	1900*	313
Ramp	20	78.33	2000	60		
5	1460	102.67	2000	60	2900*	603
Ramp	20	103.00	2400	80		
6	1460	127.33	2400	80	3400*	865
Ramp	20	127.67	2600	100		
7	1200	147.67	2600	100	4053	1103
Ramp	30	148.17	idle	0		
8	110	150.00	idle	0	0	idle
Total Cycle Time		**2.5 hrs**				

In normal circumstances this cycle will be run 3 times sequentially for a complete engine BIPO

Note: (*) The dyno torque values (in Nm) have been calculated from the expected full load at that particular state speed (normally determined from reference specification or initial test power curve).

The torque values stated here are calculated from post-CS Gateway WAVE data (b309) and will be further revised during DD phase. Also, the part-load torques have been rounded to the nearest 100Nm, to facilitate easier visual monitoring of the torque stability by the test operator.

The test cycle sequence is represented graphically below:



9.4 Test Cycle Logging

For this test, the data logging requirements are:

- Continual 1Hz from start of test (including initial priming)
- Averaged Key point log requirements:
    - 30s averaged log for stable cycle stages only (i.e. not transition ramps) as indicated in table below
    - Averaging period to commence 35s before end of stage and next transition ramp

Key point logging timing and conditions :

KEY POINT (#)	KP1	KP2	KP3	KP4	KP5	KP6	KP7	KP8
30s AVERAGED LOG START TIME (s)	205	1685	3165	4645	6125	7605	8825	8965
ENGINE SPEED (rpm)	Idle	1000	1300	1560	2000	2400	2600	2600

9.5 Test Procedure

First cycle start only :

9.5.1 Check fuel supply from test bed supply to engine is open

9.5.2 Rotate engine for two full revolutions by hand to checking for any excessive friction / tight spots etc. that may indicate an internal engine fault.

9.5.3 Record test bed running hours and set cycle hours to zero

9.5.4 Check that default test bed warnings and alarms are set and activated

9.5.5 Initiate logging at 1Hz (for lube system priming monitoring)

9.5.6 Switch ignition on and **without cranking** check that lube priming pump runs and oil gallery pressure rises above the minimum oil pressure for start (1 bar g. unless otherwise specified)

9.5.7 Allow pump to run for 1 minute to ensure full circulation and priming.

9.5.8 Switch ignition off, pause logging and wait for 5 mins for oil to drain down.

9.5.9 Recheck oil level in tank and add further oil as appropriate to take oil level up to Max. (record all additions in logbook)

9.5.10 Restart logging and switch ignition on

9.5.11 If engine control system allows cranking of the engine without firing:

- Crank the engine to ensure the fuel system is primed (either HP fuel pump pressure or rail pressure begins to rise), then crank and fire as normal

9.5.12 If engine control system does not enable cranking without firing, then :

- Crank and attempt engine start as normal whilst monitoring the HP Fuel pump and rail pressure

9.5.13 In either case if the engine does not fire or achieve the required fuel pressure within 30s stop cranking. Initial start attempt should be made with the electric starter. Subsequent start attempts should be made using the air starter if equipped. Do not attempt more than 3 x 30s failed start cranks to prevent damage. Stop and contact responsible test engineer for further instruction.

9.5.14 Once a successful start has been achieved, Idle the engine for 5 mins. whilst monitoring the engine for any leaks, noise, or any other abnormal signs of concern. Check all instrumentation is functional and responding correctly.

9.5.15 After 5 mins, stop engine and pause logging

9.5.16 Enter test cell and inspect the engine and connected test bed conditioning systems carefully for any leaks or faults. Record any observations in the engine logbook. Contact the responsible test engineer for further instruction if any issues are found.

9.5.17 After the engine has been stopped for a minimum of 5 mins. recheck the oil tank level and add further oil as appropriate to take oil level up to Max. (record all additions in logbook).

9.5.18 Restart logging and switch ignition on crank and fire engine and initiate the BIPO test sequence to commence the first BIPO cycle. Verify that Key point averaged logs are being recorded as described in 9.4 above.

9.5.19 On completion of the first complete cycle, stop the engine and logging and repeat in-cell visual inspection of engine before proceeding to cycles 2 and 3

Subsequent cycle starts :

9.5.20 Once initial priming, successful firing, and setting of the oil fill level has been completed as described above, subsequent engine starts and BIPO cycles should be carried out as follows.
9.5.21 Check test bed alarms are activated and start logging (at 1Hz)
9.5.22 Switch ignition on and **without cranking** check that lube priming pump runs, and oil gallery pressure rises above the minimum oil pressure for start (1 bar g. unless otherwise specified)
9.5.23 For cycle 2 crank and fire the engine using the air starter and commence the test sequence
9.5.24 For cycle 3 crank and fire the engine using the electric starter and commence the test sequence

Note: If engine is stopped at any time during the test sequence, start and idle for 300 seconds and allow temperatures and pressures to stabilise before resuming test stage.

Where possible engine starting should alternate between electric and air starting

10 ENGINE PASS-OFF

Following successful completion of the BIPO test cycling the engine will normally be required to undertake the following checks or inspections to pass-off that it is in a good condition for further test activities and to provide baseline start-of-test condition data for subsequent tests.

Note that in some instances the follow-on test procedure may indicate additional start-of-test tasks that are required.

10.1 Post-Test Checks

Once the break-in test cycles have been completed, the following pass-off tasks are to be completed:

EOT Requirements	• Perform EOT Power curve and record data
	  ○ Logging rate to be 1Hz
	  ○ Crankcase blow-by is to be logged during this check
	  ○ Cylinder combustion pressures to be logged if engine is equipped with heads for measurement
	Performance rating to be carried out as per ISO 1585 (for accuracy & accessories)

Oil Requirements	• Take 100ml oil sample, ensuring that it is clearly labelled • Drain oil and confirm volume removed from engine using drain and weigh method ○ Requesting engineer to confirm if drained oil can be discarded • Remove oil filter and retain for subsequent analysis (TBC)
Other Measurements *(record in build / logbook)*	• Post-test crankshaft TV performance (TBC/optional) • Cylinder leak down and compression on all cylinders - see procedure **BE-GEN-003** • Valve clearances (optional, if requested)
Checks	• Log any fluid or gas leakages ○ Photograph and record in logbook • Engine logbook is complete and up to date • Ensure any parts removed from engine during test are clearly labelled and stored safely • Retain 100ml coolant sample • Review all BIPO data and confirm that engine is signed-off prior to commencing durability test or removing from test bed

Responsible test engineer is to review all data before the engine is removed from the testbed or commences its follow-on test.

10.2 Pass / Fail Criteria

The following criteria should be used as a guide to define if an engine has passed or failed:

Parameter	Unit	Value
Engine Power	kW	Within ±5% of target curve
Engine Torque	Nm	Within ±5% of target curve

Main Gallery Oil Pressure	kPa	TBC
Cylinder Combustion Pressures	Bar	TBC
In-Cylinder Leakage Check	%	Typically, within +5% of SOT and <20%
Oil Consumption	g/hr	TBC
Crankcase Blow-by	L/min	TBC

If the engine fails any of the conditions the measurement may need to be repeated (test engineer to advise)

In addition, check that :

- No visible oil or coolant leaks
- No visible fuel leaks
- No visible exhaust gas leaks or evidence of component heat damage
- All components meet functional requirements at EOT
- ECU must be free of all fault codes (other than those which occur due to the absence of supporting vehicle systems / interface)

If any engine fails the BIPO test, it is to be reworked and re-BIPO'd before being used for further engine testing.

11 REPORTING REQUIREMENTS

A one-page summary document should be prepared to include and summarise the following

- Test hours completed
- Engine power curve data
- Additional engine health check data including, oil pressure, blow-by, compression and leak down data
- Oil additions & consumption
- Additional key engine parameter data (TBA)
- Brief summary of any engine or component failures (with test history of time, hours, failure mode etc) or replacements (with reason)
- Test outcome (Pass/Fail/Re-test)

Additionally, the data pack including the following should be archived :

- Completed logbook,
- All data recordings (including any retained shutdown logs),
- Electronic data from any measurements (or scanned sheets where not),
- All photos of test installation, engine, additional instrumentation, or conditioning components

12 ENGINE TEARDOWN

The engine is not to be torn down following BIPO unless explicitly requested by the requesting engineer.

Do not disturb or remove any components other than those for normal servicing unless explicitly requested (and record in logbook).

If oil has been drained and the engine is to be stored or shipped elsewhere ensure there is a clear indication on the engine that it 'REQUIRES OIL FILLING'

Ensure all open engine fluid interface connections are suitably plugged and bagged to prevent contamination

13 APPENDIX

APPENDIX 1 – EXAMPLE OF ENGINE BUILD MEASUREMENT LIST

Details of pre- and post-test component inspection measurements will be advised in a later update of this procedure once relevant detail design and analysis activities are complete.

Wherever possible and appropriate pre-test measurements should be made during the engine build process.

Example measurements are shown in the table below:

COMPONENT	MEASUREMENT	PRE-TEST	POST-TEST
Crankcase	Inner diameter of cylinder bore (3 locations)	X	X
	Inner surface finish of cylinder bore (3 locations)	X	X
	Profile of longitudinal liners for determination of TDC wear		X
	Dimensional measurement of bench supports (Main Bearings)	X	X
	Check alignment of main bearing housings	X	
	Main bearing bore diameter (without bearing)	X	
	Main bearing bore diameter with bearings	X	
	Centre main bearing thrust width	X	
	Flatness of flame face (deck face)	X	X
	Roughness of cylinder head flame face	X	
	Protrusion of cylinder liners from engine block	X	
Piston and Rings	Selection diameters (Gauge point)	X	X
	Gudgeon pin bore diameter	X	X
	Ring groove width (top)	X	X
	Ring groove width (second)	X	X
	Ring groove width (oil control)	X	X
	Mass (excluding rings)	X	
	Mass (including rings)	X	X
	Tangential load (top)	X	X
	Tangential load (second)	X	X
	Tangential load (oil control)	X	X
	Thickness (top)	X	X
	Thickness (second)	X	X
	Thickness (oil control)	X	X
	Fitted gap measured in ring gauge (top)	X	X
	Fitted gap measured in ring gauge (second)	X	X
	Fitted gap measured in ring gauge (oil control)	X	X
	Piston stand proud	X	
Piston Pins	Outer diameter of pin in three positions	X	X
	Roughness	X	
Crankshaft	Crank journal and rod pin diameters (main and big end)	X	X
	Crank journal and rod pin roughness (main and big end)	X	X
	Crank thrust width	X	
	Crank thrust surface roughness	X	
	Axial clearance of main and big end bearings	X	
Rods	Big end diameters	X	X
	Big end diameters with bearings fitted	X	X
	Big end surface roughness	X	
	Small end diameters	X	X
	Small end width	X	X
	Bore parallism	X	
	Mass	X	
	Small end roughness	X	X
	Perpendicularity	X	
Main and Big End Bearings	Thickness	X	X
	Protrusion under load indicated on drawing (crush)	X	
	Inner diameter of half bearings installed in rod big end and main bearings (tighten to specification)	X	X
Cylinder Bores (with head plate fitted if required) [Bore distortion]	Cylindricity (all cylinders)	X	X
	All Cylinders – 2nd, 3rd, 4th order	X	X
Cylinder Head	Gas face flatness	X	X
	Gas face roughness	X	
	Valve guide diameters	X	X
	Valve stand proud or stand down	X	X
	Camshaft bore thrust width and finish	X	
	Valve guide to seat run out	X	X
	Camshaft bearing carrier diameter	X	X
Cylinder Head Fasteners	Length	X	X
Valves	Stem diameter	X	X
	Stem roughness	X	X

	Stem to seat run out	X	X
	Valve height	X	X
	Seat profile	X	X
Camshaft	Journal diameters	X	X
	Cam thrust width	X	
	Cam roughness	X	X
	Cam hardness	X	
	Valve lift	X	
Valve Tappets	Diameters	X	X
	Roughness	X	
Valve Springs	Free length of spring	X	X
	Spring rate	X	
Gear Drive	Backlash	X	X

Note fastener crack-off and back-to-mark torques to be noted on critical fasteners only *[TBA].*

14 REVISION HISTORY

Issue	Date	Description
01	14^{th} Sept. 2021	Initial Draft

TEST CELL SET UP

Test No.	BE-GEN-001	Engine Variant	GEN1	Issue level & Date	Issue 01 14 Sept. 2021

1 AIM

This procedure describes the default test cell set-up, configuration and operation that should be used as a standard basis for all BE1500 durability test activities.

It may also be used as a starting basis for functional development engine test installations but with appropriate modifications specified depending on the particular development activities being undertaken.

Note that this is an initial draft that will be further developed as the engine design, analysis and simulation, DVP test requirements and test facility plans progress through the definitive design phase.

2 INTRODUCTION

2.1 General Details

The BEML BE1500 engine is a new 25 litre V12 twin-turbocharged Diesel engine for application in a new armoured military vehicle. The engine bore and stroke is 138mm x 140mm giving a displacement of 2.09 L/cylinder (total displacement 25.13 L). Bank angle is 90°. The firing order is 1-12-5-8-3-10-6-7-2-11-4-9, with uneven 90 & 30 deg. firing intervals and compression ratio of 15.5:1.

Mean operating cylinder pressure (Pmax) is 180 bar (targeted by WAVE), with Pmax max. at 190 bar

Target engine rated power is 1003kW at 2600rpm, BSFC 188 g/kWh (@sea level-DD1) and peak torque is 4794Nm @ 1560 rpm. Engine Idle speed is 830 rpm,

The prime FIE is a Liebherr CRDi system operating with a rail pressure of up to 2200 bar, pressurized from two rear geartrain driven pumps. A low-pressure fuel lift pump is driven from the front geartrain. Note that this procedure does not currently consider test operation with other backup electronic and mechanical FIE systems. The EMS will also be provided by Liebherr

Turbocharging is provided by two TEL turbochargers operating in parallel (one/per bank). Exhaust manifolds are fabricated from Stainless Steel with bellow for thermal expansion. Turbo oil feed & drainpipes are also fabricated from stainless steel

The engine is designed with a dual circuit cooling system - High Temperature (HT) & Low Temperature (LT) with separate pump rotor arrangements driven from the same shaft from the front geartrain. Cylinder block, cylinder head and the majority of charge air cooling is provided by the HT circuit. The LT circuit provides cooling for the Fuel cooler, engine and transmission oil coolers, turbo centre-housings and further lower temperature charge-air cooling. Each circuit has its own expansion tank and feeding to separate radiators for heat rejection.

The engine lube system is a dry sump system with a combined scavenge and pressure pump driven from the front cranktrain. The dry sump oil tank is mounted on the front of the engine and provides initial de-aeration of the scavenged oil. The engine breathing is also facilitated by the oil tank with the outlet vent pipes then passing into a CCV oil separator system mounted in the engine Vee. Note also that as a precaution GEN1 engine will be specified with a tertiary oil cyclone-type separation system between the two.

The valve train is a 4-valve OHV-pushrod design with rockers and bridge pieces actuating each pair of valves. It will be necessary to measure the engine's valve clearances during the durability testing for which a recommended process will be provided.

It is intended that all durability tests will take place using the vehicle spec. self-cleaning air filter assembly (unless otherwise notified). The same unit may be used for all tests, but the assembly should undergo a complete cleaning cycle and inspection prior to commencing each test. Total number of test hours completed must be recorded in the test bed logbook.

2.2 Engine Orientation

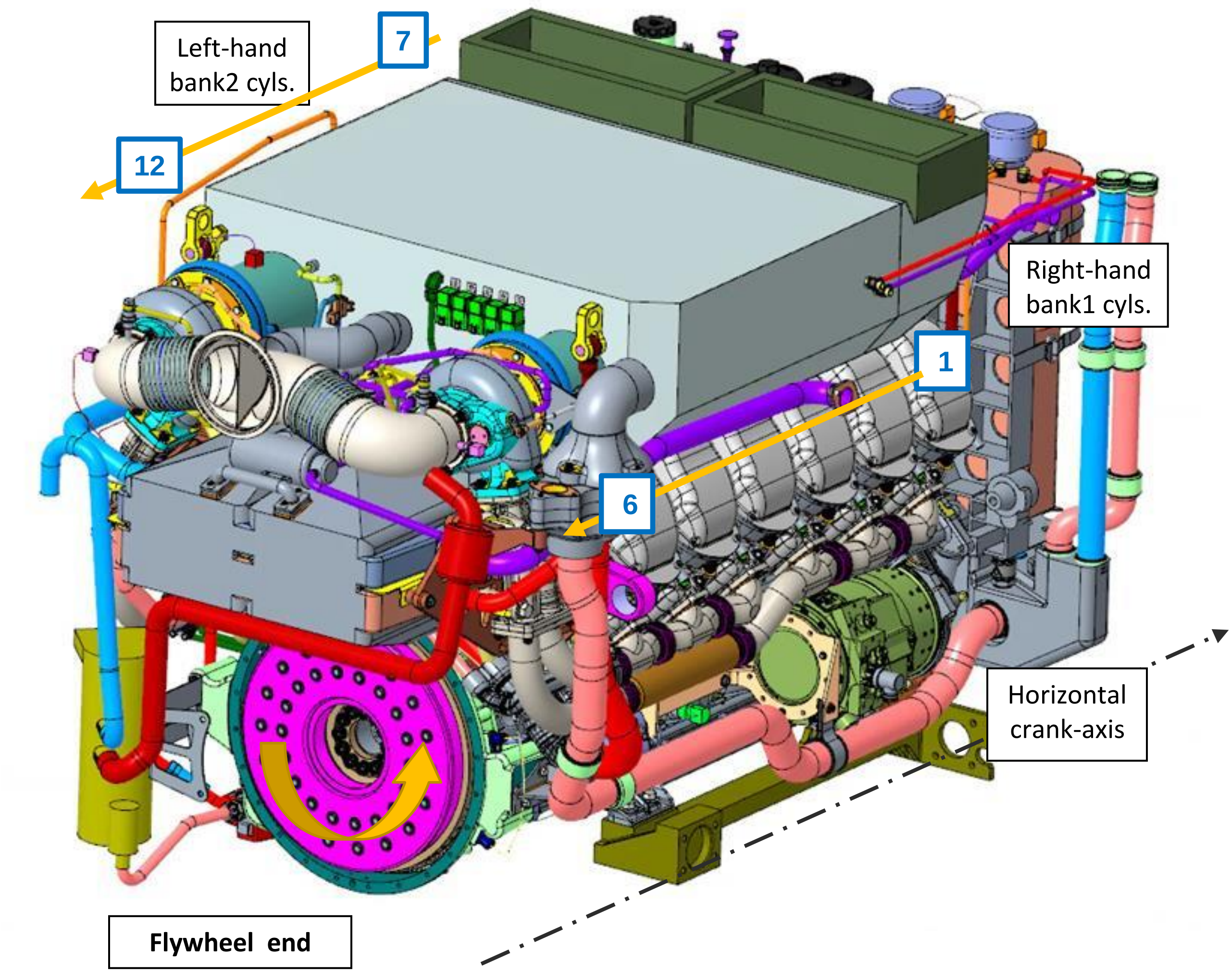


FIGURE 1 - LATEST ENGINE MASTER ASSEMBLY CAD IMAGE VIEWED LOOKING ONTO FLYWHEEL (REAR) END FROM RIGHT HAND SIDE

The left-hand & right-hand banks are defined when viewed from the flywheel-end of the engine as shown in Figure 1 above. Cylinders are numbered from front to rear starting with cylinders 1 to 6 on the right-hand (Bank 1) side. Bank 2 is the left-hand bank of cylinders starting with cylinder 7 at the front to 12 at the rear, as shown.

Crank rotation is anti-clockwise when facing the Flywheel end (clockwise facing crank damper end)

3 ENGINE AND TEST BED PREPARATION / INSTALLATION

3.1 ENGINE MOUNTING

The engine should be mounted on the test bed installation with the engine crank axis vertically aligned with the dyno shaft axis, and with the shaft mounting flanges at the engine end and dyno end parallel to each other.

The engine should be supported via its vehicle engine mounting brackets resting on Cushyfoot (or similar) anti-vibration mounts on bespoke mounting pillars. Selection of appropriate AV mounts and the pillar design must consider the total installed engine mass (including all ancillaries and fluids) and reaction torques from engine acceleration / deceleration. This is especially important as engine stall testing will be undertaken during some of the durability test cycles.

The optimum mounting position is at the height of the centre of gravity of the engine, or engine and gearbox unit, with four Cushyfeet equally spaced from the centre of gravity (two along each side). The mounts should be positioned as close to the engine block as the ancillaries will permit in order to reduce the coupling/roll frequency. The stiffest plane of the AV mount should be aligned along the crank/driveshaft axis.

3.2 DYNO & DRIVELINE

The current assumption is that all GEN1 test facilities (at Ricardo, BEML & CVRDE) will be using hydraulic (water-brake) dynamometers with no motoring capability.

The test facility will need to be configured and suitably specified for appropriate dyno speed and load control and provide appropriate cooling management, dyno + shaft mounting, and drive shaft system balancing, stiffness, and servicing requirements.

Note that the vehicle powertrain will have an integrated flywheel and Geislinger IGB decoupler arrangement mounted on the rear end of the engine crankshaft. As the IGB is designed to interact with the vehicle gearbox (only) it will not be used on the test bed installations. Therefore, in order to simulate the correct driveline inertia with the test bed configuration (to ensure the crankshaft loading is representative) a bespoke flywheel design and drive shaft coupling will be required (see Figure 2).

Each test bed's dyno and selected drive shaft inertias and masses will be required to enable appropriate flywheel coupling mass and inertias to be calculated (i.e., so that the complete test bed driveline assembly replicates the vehicle driveline conditions at the engine). Note that this may mean that bespoke flywheel / adaptor assemblies are required for each test bed installation.

There should be a small horizontal offset introduced to give a 1-1.5° angle on the prop shaft U/Js to ensure they are suitably 'worked' (see Figure 2). Horizontal misalignment is typically easier (than vertical) as it can be achieved on the test bedplate cross slides rather than having to add packing pieces to a fixed height installation.

The dynamometer's static torque calibration should be regularly checked at scheduled intervals (suggest a weekly check initially for new installation)

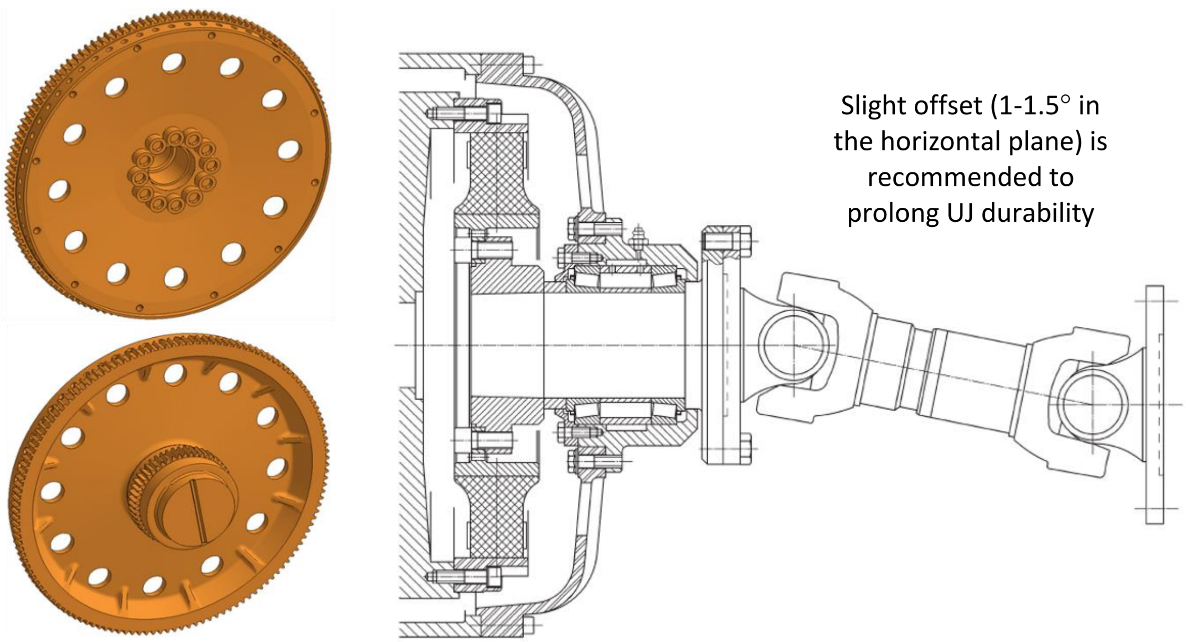


FIGURE 2 - TEST BED FLYWHEEL DESIGN AND EXAMPLE PTO / FLYWHEEL / SHAFT ADAPTOR ARRANGEMENT

3.3 COOLING

The test bed installation will need to provide a supply of test facility 'recirc' cooling water, capable of maintaining representative, stable HT & LT engine system coolant temperatures throughout all test procedure running conditions (transient and steady state).

See appendix 11.1 below for schematic diagram indicating where the test bed coolers should interface with the engine.

Current performance simulation shows a peak HT radiator heat rejection of 584 kW and Peak LT radiator heat rejection of 385kW. It is recommended that the test bed cooling is slightly over-spec'd (e.g.,+10% compared to vehicle cooler specification) to enable good control during transient temperature conditions. This will also enable the pressure drop across the test bed coolers to be matched to the vehicle by installing appropriate restrictors (i.e., adjustable valve or fixed orifice) in the two engine circuits.

The test bed cooling circuit restriction must not exceed expected vehicle radiator circuit restriction (risk of cavitation).

The engine and test bed coolant flow must always be monitored via sensors to ensure correct priming and function of the cooling system on start-up and during testing. A sight glass may be specified for some tests (e.g Thermal cycling) installed between the engine's coolant outlet and HT cooler.

Note that the engine's cooling system will be pressurised during running by both the coolant expansion with temperature and also additional pressurised air from the boost system. A means of depressurisation of the system when stopped is currently being developed and the process for the test bed depressurisation will be advised in the next design phase.

The engine-side cooling system components (including any additional instrumentation) must be capable of withstanding the design system pressures and temperatures.

HT coolant setpoint target temperatures will be specified from the engine coolant outlet position unless otherwise stated. The test bed cooling systems control system (PID controllers) will need to be appropriately commissioned and tuned to maintain the required setpoints prior to the start of any durability test cycling.

Current simulation of cooling pump flow rate is 900 l/min (HT) & 441 l/min (LT).

Test bed installation should use intended vehicle HT & LT expansion tanks where possible. Note that if the test bed cooling circuit volume varies greatly from the vehicle it may be necessary to stipulate different fill levels for test bed usage (due to volume expansion).

It is intended that the majority of testing will be carried out using the Summer spec. as standard. However, the cooling system should also be capable of running with the Winter-spec. Water/Ethylene Glycol mix if specific testing is required and requested.

3.4 Lubrication / CCV

The engine is equipped with an oil system priming pump to ensure that the Crankshaft TV damper is filled and pressurized with oil prior to engine start-up. The test bed system should automatically monitor that the pump system is functioning correctly by verifying an appropriate engine main oil gallery pressure has been reached <u>before</u> enabling engine cranking. This function must be active for both electric and air starts and for all programmed or manual starts.

The engine's dry sump oil tank will normally be mounted on the front of the engine. In certain circumstances, it may be necessary to remotely mount or adjust the tank position (e.g. to enable instrumentation to be applied to the crank nose / TVD for TV measurements or encoder for combustion analysis). This will also require modification of the tank oil feed and return pipes. Further details will be developed during the definitive design phase.

The test bed tank should provide a means of electronically or visually monitoring the dynamic internal oil level e.g., using an external sight tube with camera.

It is recommended that a manual drain valve is added to the bottom of the test bed's oil tank so that regular oil samples may be taken in a timely and repeatable way.

The engine's CCV system should enable blowby flow meters to be installed in the oil tank breather outlet pipes and secondary separator outlet for scheduled health checks during the tests. It is also recommended that initial GEN1 test also have catch cans permanently installed (upstream of the meter positions) as a precaution should high oil carryover occur. If installed these should be monitored (by in-cell camera and checked and emptied during appropriate service breaks (weigh and record any fluid content).

3.5 Fuel

GEN1 testing should be carried out using DHPP-A diesel fuel unless stated otherwise in test procedure or specific development test instructions.

Fuel temperature at the LPFP inlet should be controlled to 40 ±5 deg. C unless otherwise stated

The materials used in the fuel conditioning module must adhere to any FIE supplier material compatibility requirements (e.g. no Zn or Cu material as this can leach into the fuel causing problems with injectors) – typically stainless-steel pipework and fittings are used throughout.

3.6 Combustion Air / Charge Air

Ricardo standard practice is not to couple the combustion air supply directly to air intake but instead to flood the area around the dirty air intake duct with excess conditioned air and then allow the engine to inhale what is needed (i.e. at close to ambient pressure).

The maximum engine air flow at rated power is 5400 kg/h and the system will need to be able to supply a flow of temperature-conditioned air greater than this value to account for conditioned air leakage between the conditioning unit outlet and engine inlet. a combustion air supply requirement of 6250 kg/h (+15%) should be adequate.

Specific humidity control is not a mandatory requirement, but the facility should be able to limit to a maximum humidity of around 80% RH @ 30 deg. C, especially during seasonal high ambient humidity conditions.

A ‘reference’ engine inlet air temperature for performance checks should be defined within 25-35 deg. C range at which the combustion air supply temperature can be controlled to within a +/-2 deg. C accuracy, at all test bed ambient and cooling water temperatures and facility cooling utilisation conditions.

Independent Charge Air temperature control may be achieved by adjustment of heat rejection in test bed LT circuit

- Target control temperature should be specified and measured from the test LT cooler outlet instrumentation position

3.7 Exhaust

The test cell exhaust system must be design and attached to the engine’s single exhaust outlet in such a way that it does not impart any additional loading on the engine component structures, neither due to its weight, dynamic vibration, or thermal expansion.

Long straight sections must be adequately supported and should have thermal expansion isolators included.

For durability testing it will be preferable that all engine out exhaust gas instrumentation (temperature, pressure, smoke and emissions) may be located in the test bed system rather than in the engine’s exhaust outlet. This will enable the same instrumentation to be used for multiple tests and reduce the risk of engine component failures due to instrumentation-related modifications.

The test bed exhaust system should have a pressure regulating valve included that is capable of controlling the exhaust back pressure to both the nominal max. condition of 0.1 barg and also simulate the fording condition of 0.3924 barg max. The valve setting must be capable of being completed while the engine is running at its rated power condition.

The maximum predicted turbine outlet gas temperature is <640 deg. C

- Cooling fans/ air movers may be required to be directed towards the exhaust manifolds and turbochargers during testing. These must have divergent wide-flow outlets and not be of 'spot'-cooler type design which can induce differential thermal expansion / contraction and lead to component failures.

3.8 ENGINE STARTING

The test bed installation and control system must be capable of selecting between engine starting via electric motor start and the air starter, as required by the operator and/or automated test sequence.

The number of electric and air starter actuations must be counted and logged.

The automated test sequence should allow for either of the systems to be overridden in case of a number of continuous failed starts.

3.9 VIDEO MONITORING

In-cell camera(s) should be available to enable remote monitoring and recording of the sump oil level sight tube, breather system (catch can and breather system windows - if fitted) and other general condition monitoring.

3.10 FLUID SPECIFICATIONS

The engine's fluid specifications for test bed are as follows:

<table>
<tr><th>Fluid</th><th colspan="2">Specification</th><th>Engine Volume</th></tr>
<tr><td>Oil</td><td colspan="2">Mobil 1 FS X2 5W-50</td><td>60-70 litres (TBC)</td></tr>
<tr><td rowspan="2">Coolant</td><td>100% water with inhibitors</td><td>Summer (Default)</td><td rowspan="2">HT – 90.8 litres, LT – 51.4 litres</td></tr>
<tr><td>60:40 Ethylene glycol/water mix</td><td>Winter</td></tr>
<tr><td>Fuel</td><td colspan="2">DHPP-A</td><td>N/A</td></tr>
</table>

4 INSTRUMENTATION

The following is an initial draft of a standard minimum list of instrumentation that is to be applied to all BEML GEN1 **development and durability engine test installations**.

Note that individual test procedures may require additional instrumentation (but for durability tests changes will be minimal):

ID#	Instrumentation	Type	Medium	Sensor	Location
			Temperatures		
1	Cell ambient temperature	T	Air	3mm K-type	Test Cell
2	Tank bulk oil	T	Oil	3mm K-type	Oil tank (lower)
3	Main gallery - pressure switch location	T	Oil	3mm K-type	Block (via T/P adaptor)
4	Engine Inlet	T	Coolant	3mm K-type	Pump inlet (TBC)
5	Engine Outlet	T	Coolant	3mm K-type	Outlet pipe to thermostat
6	WCAC (HT) out	T	Coolant	3mm K-type	CAC coolant outlet pipe
7	WCAC (LT) out	T	Coolant	3mm K-type	CAC coolant outlet pipe
8	Test bed HT cooler inlet	T	Coolant	3mm K-type	Top hose / Rad in
9	Test bed HT cooler outlet	T	Coolant	3mm K-type	Bottom hose / Rad out
10	Test bed LT cooler inlet	T	Coolant	3mm K-type	Cooler inlet
11	Test bed LT cooler outlet	T	Coolant	3mm K-type	Cooler outlet
12	Turbo run on pump out	T	Coolant	3mm K-type	Turbo run on pump
13	Air cleaner inlet	T	Air	3mm K-type	Air cleaner inlet duct
14	LH Compressor out (TBC)	T	Air	3mm K-type	Comp.out pipe
15	RH Compressor out (TBC)	T	Air	3mm K-type	Comp.out pipe
16	Plenum RH Bank	T	Air	3mm K-type	Intake manifold
17	Plenum LH Bank	T	Air	3mm K-type	Intake manifold
18	Runners - bank-to-bank monitoring (#cyls. TBC)	T	Surface	Surface mount	Exhaust Manifold (skin)
19	Pre-Turbo RH Bank	T	Exhaust	6mm K-type	Turbo / Manifold (TBC)
20	Pre-Turbo LH Bank	T	Exhaust	6mm K-type	Turbo / Manifold (TBC)
21	Post-Turbo RH Bank	T	Exhaust	3mm K-type	Turbo / Exh.outlet (TBC)
22	Post-Turbo LH Bank	T	Exhaust	3mm K-type	Turbo / Exh.outlet (TBC)
23	Exhaust outlet (pre-restriction valve)	T	Exhaust	3mm K-type	TBC
24	Turbine flange skin temp. (RH Bank)	T	Surface	Surface mount	Turbine flange (skin)
25	Turbine flange skin temp. (LH Bank)	T	Surface	Surface mount	Turbine flange (skin)
26	LP Fuel pump inlet	T	Fuel	3mm K-type	Supply line from rig

27	Spill return	T	Fuel	3mm K-type	Return line to rig
28	TV Damper peak temp (TBC)	T	Surface	IR	Infrared on TVD (TBC)
29	Cylinder metal temperature RH Bank (TBC)	T	Surface	Surface mount (TBC)	Cylinder head, position TBC
30	Cylinder metal temperature LH Bank (TBC)	T	Surface	Surface mount (TBC)	Cylinder head, position TBC
			Pressures		
31	Tank CCV Outlet	P	Oil	0-5 bar gauge	Oil tank upper (e.g. Cap) or CCV outlet pipe
32	Main gallery - pressure switch location	P	Oil	0-10 bar gauge	Block (via T/P adaptor)
33	Engine Outlet	P	Coolant	0-10 bar gauge	Outlet pipe to thermostat (TBC)
34	Test bed HT cooler inlet	P	Coolant	0-6 bar gauge	Top hose / Rad in
35	Test bed HT cooler outlet	P	Coolant	0-6 bar gauge	Bottom hose / Rad out
36	Test bed LT cooler inlet	P	Coolant	0-5 bar gauge	Cooler inlet
37	Test bed LT cooler outlet	P	Coolant	0-5 bar gauge	Cooler outlet
38	HT Expansion tank	P	Coolant	0-5 bar gauge	Expansion tank cap (TBC)
39	LT Expansion tank	P	Coolant	0-5 bar gauge	Expansion tank cap (TBC)
40	Air cleaner inlet	P	Air	0-5 bar gauge	Air cleaner inlet duct
41	LH Compressor in (TBC)	P	Air	0-5 bar gauge	Comp.in pipe
42	LH Compressor out (TBC)	P	Air	0-5 bar gauge	Comp.out pipe
43	RH Compressor in (TBC)	P	Air	0-5 bar gauge	Comp.in pipe
44	RH Compressor out (TBC)	P	Air	0-5 bar gauge	Comp.out pipe
45	Plenum RH Bank	P	Air	0-5 bar gauge	Intake manifold
46	Plenum LH Bank	P	Air	0-5 bar gauge	Intake manifold
47	Exhaust outlet (pre-restriction valve)	P	Exhaust	0-5 bar gauge	TBC
48	Fuel filter inlet	P	Fuel	TBC	TBC
49	Fuel filter outlet	P	Fuel	TBC	TBC
50	LP Fuel pump inlet	P	Fuel	0-5 bar gauge	Supply line from rig
51	Spill return	P	Fuel	0-5 bar gauge	Return line to rig
52	Pre-oil separator pipe 1 (TBC)	P	CCV	0-5 bar gauge	Tank vent pipework
53	Pre-oil separator pipe 2 (TBC)	P	CCV	0-5 bar gauge	Tank vent pipework
54	Crankcase Pressure(s) (TBC)	P	CCV	0-5 bar gauge	TBC
55	Kistler cylinder pressure - Minimal cyls. (TBC)	P	Combust.	Kistler (TBC)	e.g. 1/bank?
			Flow		
56	HT Radiator flow	F	Coolant	0-1000l/min	Top / Bottom hose (TBC)

57	Flow	F	Fuel	TBC	Supply line from rig
58	Tank Breather flow (blowby)	F	CCV	0-600l/min	Oil tank outlet pipe(s) (TBC)
59	Fresh air make up flow (TBC)	F	CCV		Make-up air inlet pipe
Other					
60	Barometric Pressure (abs)	P	Test cell	0-5 bar gauge	Test cell
61	Intake air humidity	H	Test cell		Test cell
62	Fuel Consumption	F	Fuel		Conditioning rig supply
63	Post-Turbo RH Bank - Lambda sensor	L	Exhaust	Lambda	Turbo / Exh.outlet (TBC)
64	Post-Turbo LH Bank - Lambda sensor	L	Exhaust	Lambda	Turbo / Exh.outlet (TBC)
65	Exhaust Smoke (qty. TBC)	Smk	Exhaust		Combined exh. Outlet
66	Turbocharger Speed RH Bank	N	Exhaust		Turbocharger
67	Turbocharger Speed LH Bank	N	Exhaust		Turbocharger
68	Crank position sensor for TV measurement	°	Cranktrain	Position sensor	60-2 missing teeth wheel (TBC)
69	Crank angle indicator for Combustion analysis	°	Cranktrain	Position sensor	Encoder wheel / Geartooth speed sensor (TBC)
70	Flywheel ring gear sensor	°	Cranktrain	Position sensor	Geartooth speed sensor (TBC)
71	Starter motor relay voltage/current (TBC)	V/C	Elect'l	Voltmeter / Current clamp	Starter motor relay
72	Air Start control valve voltage/current (TBC)	V/C	Elect'l	Voltmeter / Current clamp	Air starter control valve
73	Generator current RH Bank (TBC)	C	Elect'l	Current clamp	Generator 1
74	Generator current LH Bank (TBC)	C	Elect'l	Current clamp	Generator 2
75	Wastegate PRV RH Bank (TBC)	V/C	Elect'l	Voltmeter / Current clamp	Wastegate 1
76	Wastegate PRV LH Bank (TBC)	V/C	Elect'l	Voltmeter / Current clamp	Wastegate 2
77	Hot shutdown pump activated (TBC)	V/C	Elect'l	Voltmeter / Current clamp	Hot shutdown pump control valve
78	Cylinder block	A	Accel.	Accelerometer	Cylinder block (location TBC)
79	Oil catch cans	-	CCV	Volume	Tank CCV outlet (x2)
80	Oil catch can	-	CCV	Volume	Post-separator

Additional instrumentation requirements may be required for specific tests (see individual test procedures).

Further requirements may need to be added pending further engagement with component suppliers.

Also, it is considered advisable to build-in capability for use of diagnostic instrumentation such as emissions / lambda sampling points, cylinder pressure in selected (multiple) cylinders with provision for fitment of encoder for combustion analysis and other additional component temperature and pressure channels (TBA).

Roving/relocatable thermocouples and appropriate logging channels should also be provided for monitoring external engine temperatures (positions and number TBA)

5 ECU PARAMETER LOGGING REQUIREMENTS

ECU parameters requiring logging by default for each test will be specified during definitive design phase

Temperature		Pressure		Other	
	TBA		TBA		TBA

6 TEST SAFETY SHUTDOWN LIMITS

For all testing, safety limits will need to be applied to critical parameters (TBA - see typical list of parameters below, shutdown limits and warning values will be advised during definitive design phase):

Channel	Unit	Max. limit	High shutdown	High warning	Low warning	Low shutdown
EngineSpeed	rev/min					
Dyno Speed	rev/min					
Dyno Torque	Nm					
tCell Ambient	°C					
tAir_Intake	°C					
tComp In *	°C					
tComp Out *	°C					
pabsComp Out (abs) *	kPa					
tInMan *	°C					
tTurbine_In *	°C					
tTurbine_Out *	°C					
pgTurbine_Out *	kPa					
tCoolant_Out	°C					
pgCoolant_ExpTank	kPa					
qCoolant	l/min					
tOil_Gallery	°C					
pgOil_Gallery (gauge)	kPa					
tOilTank	°C					

Limits and warnings TBA

tFuel_HPPump_In	°C					
pgFuel_HPPump_In (gauge)	kPa	200	200	190	60	50

Note: * - Both banks

Further details of Limits and shutdown / warning parameters and appropriate values will be added as the definitive design phase progresses

- Output from speed sensors on dyno and engine should continually compared to detect for engine, dyno or dyno shafts / coupling failure.

7 PRE-TEST ACTIVITIES

Prior to commencing test on a new installation ensure that a 100ml sample of the Oil and Coolant is retained and that the site fuel stock has also been sampled (otherwise retain 500ml fuel sample for analysis).

Test installation must be thoroughly safety-checked.

In most cases the installed engine will require a Run-in to be completed (see document **BE-GEN-002 – BIPO)**.

Record the calibration reference ID and current dyno running hours in test logbook.

Further specific instruction for each durability test will be advised in the appropriate test procedure document.

8 WARM-UP SEQUENCE

Provision should be made for a separate automated test sequence which can be run in preparation for durability test cycling following a cooled engine restart.

The warm-up sequence should not count running time as test time (but still logged against engine & dyno running hours)

9 TEST MONITORING / REPORTING REQUIREMENTS

The test bed logging system should be configured so that logging may commence when ignition is switched on (not necessarily on engine start).

Some short lube-system priming activities require 10Hz logging rate but predominantly logging will be at 1Hz with continuous logging throughout all tests.

A 'post-mortem' system is required that in the case of a test shutdown the last 30s of data is retained (logged at 10Hz).

Additionally, averaged, or Key point logs are required at specified test cycle points – refer to individual test procedures for details.

For each test, key-point logged data is to be plotted daily to determine the engine performance is consistent.

Key-point trend data is to be plotted against a base of test hours unless otherwise specified.

For each plot, it is acceptable to show maximum 2 different variables on different scales, i.e. engine torque and power or temperature and pressure. However, these variables must be related, i.e. main gallery oil temperature and pressure.

Typical basic default parameters to plot are shown below (but additional are likely to be requested):

Engine Speed	rpm
Observed Torque	Nm
Corrected Torque	Nm
Observed Power	kW
Corrected Power	kW
Inlet Air Temperature	°C
Ambient Air Temperature	°C
Relative Humidity	%
Barometer	kPa
Correction Factor	
Fuel Temperature	°C
Fuel Flow Rate (if measured)	L/min
Fuel Pressure	kPa
Exhaust Backpressure	kPa
Exhaust Gas Temperatures (Turbine in and out / manifold surface temps.)	°C
Coolant Inlet & Outlet Temperatures (HT)	°C
Coolant temperatures (LT circuit)	°C
Coolant Pressures (HT & LT)	kPa
Oil Temperature in Main Gallery or Sump	°C
Oil Pressure in Main Gallery	kPa
MAP (Manifold Absolute Pressure)	kPa
Intake Manifold Temperature	°C
Crankcase Pressure	kPa
BSFC (Brake Specific Fuel Consumption)	g/kWh

If any measured parameter deviates from the measured value at SOT greater then ±10%, the test is to be stopped and the requesting engineer to be informed.

Refer to individual durability test procedure for details of regular scheduled checks and measurements to be performed at the start, during and on completion of their tests.

10 POST-TEST ACTIVITIES

At the completion of the schedule engine test programme ensure the following activities are completed before the engine is removed from the bed:

- Ensure all end-of-test data is recorded correctly
- Ensure data is plotted
    - Key-point trend plots for key parameters (listed in section 9 above)
    - Plots of key parameters from all scheduled engine prop. load curve health checks
- End-of test performance checks have been completed and quality of test data verified
- Archive of all 1Hz logs taken
- Archive of electronic test workbook
- List of shutdown events and action taken with relevant post-mortem logs
- List of component replacements or adjustments through test (incl. tappet adjustments)
- Summary list of all engine health measurements taken (i.e. compressions, cyl. leakages etc.)
- Oil consumption trend summary

11 APPENDIX

11.1 COOLING SYSTEM TEST BED CONDITIONING INTERFACES WITH ENGINE

The engine cooling system pipework and fittings that would normally run to and from the vehicle HT & LT radiators should be appropriately modified / adapted for the test bed cooler connections, as indicated by E/F & G/H in Figure 3 below

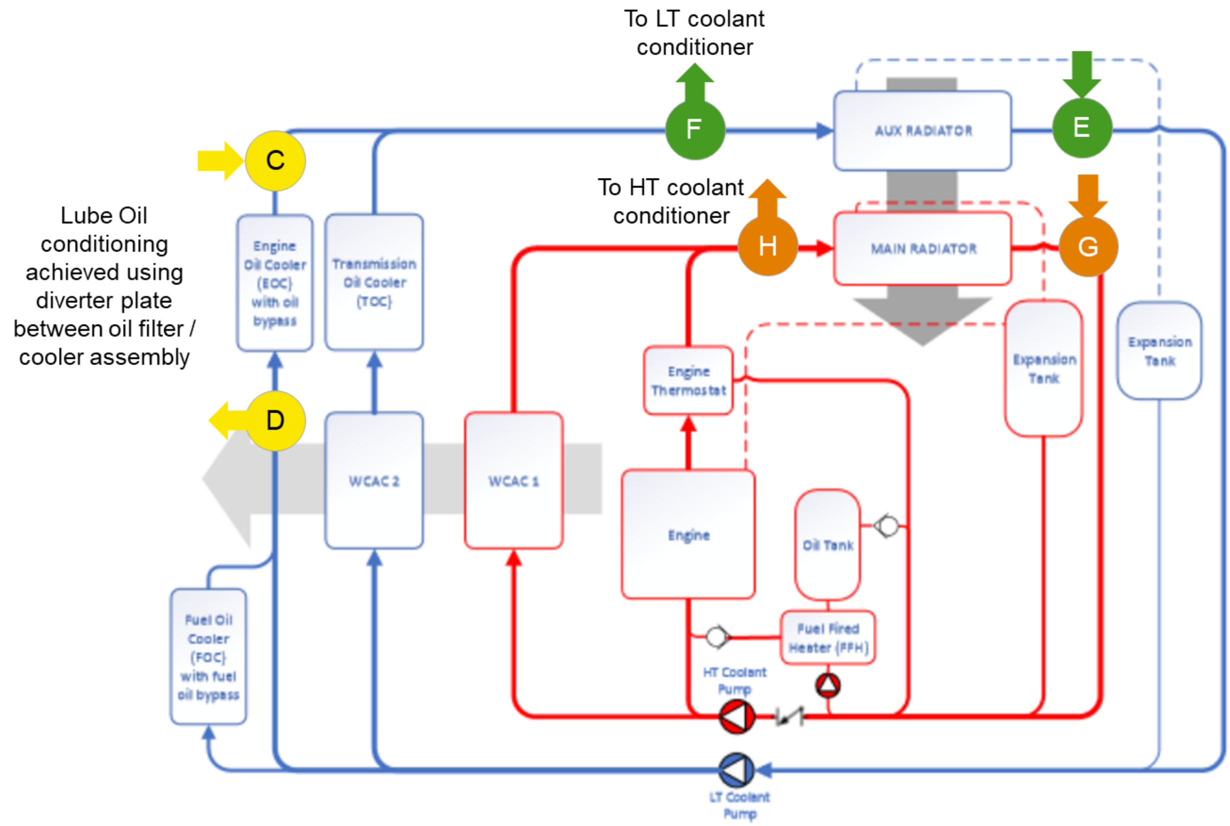


FIGURE 3 - COOLING SYSTEM ENGINE INTERFACE LOCATIONS

12 REVISION HISTORY

Issue	Date	Description
01	14th Sept. 2021	Initial Release