THERMAL CYCLING DURABILITY (500-CYCLES)

Test No.	BE-DUR-005	Engine Variant	GEN1	Issue level & Date	Issue 01 14 Sept. 2021

1 TEST OVERVIEW

The aim of this 500-cycle Thermal cycling durability test is to verify the durability and robustness of the complete engine assembly and mechanical systems to thermal stress (e.g. due to low cycle fatigue, thermal deformation, wear/damage from differential thermal expansion etc.)

The test cycle is intended to recreate in an accelerated way representative levels of Hot-Cold thermal cycling that might be experienced in normal operation (i.e. low cycle fatigue - cooled engine warm-up to max. temperature cycling).

This durability test is not intended to check the function of the engine at extreme cold conditions.

2 OBJECTIVES

The primary objectives of this test are:

- Verify and validate the robustness of the engine exhaust system (specifically exhaust manifolds and turbo assembly and their mounting / fastening arrangements) to thermal cycling.
- Verify and validate the robustness and reliability of the cooling system components (including all cooling system pipework) to thermal cycling.
- Verify and validate robustness and reliability of the lubrication system components (including all lubrication and breather system pipework) to thermal cycling.
- Verify and validate the robustness and reliability of the inlet manifold, cylinder head, cylinder head gasket, injectors, block, piston and liner structures, and their sealing.
- Validate lube oil quality and degradation from typical thermal cycling operation.
- Also, to validate thermal analysis that has been used to design the engine systems and their component's service life and overhaul requirements.

This test will also give a general indication of any underlying thermal stress or differential thermal expansion related issues that the engine assembly might experience in normal operation. Note that if concerns are found this may necessitate the need for more aggressive functional and/or thermal shock testing to extreme Hot/Cold conditions.

3 GENERAL DETAILS

This test consists of a predominantly two-phase test cycle (Heating phase & cooling phase) which is repeated 500 times. This number of cycles is considered appropriate for this product as it would be equivalent to an engine start, warm up and run up to max power of an average duration of 2.4 hrs, throughout the engine's 1200hr service life.

The overall duration of the test (in hours) will be dependent on the actual engine and test bed cooling system's heating and cooling rates achieved but it is expected to be within 175-275 hrs. duration. The rates of temperature change (especially the cooling) should not be made overly aggressive as this can lead to unrepresentative component failures.

The engine heating phase is run at the rated power condition until the engine's peak hot coolant and exhaust component temperature target ($\mathbf{T_{hot}}$) is achieved.

The cooling phase then initially commences with a brief period of high idle speed (continuous overspeed) operation followed by a drop to idle speed and increased test bed coolant heat rejection. During the latter stages of the cooling phase (once the normal test bed recirc water temperature has reduced engine coolant outlet temperature to an appropriate level – $\mathbf{T_{cool}}$), the engine is stopped and the test may require the use of an additional external chilling facility capable of introducing cold water (at circa 5 °C) to the test bed cooling circuit, in order to achieve final temperature reduction (to $\mathbf{T_{cold}}$) in a timely way.

Also,

- Oil & filter servicing is initially recommended every 125hrs due to the high temperature operation. However, pending results of the planned ongoing sample analysis, the service interval may be able to be extended.
- An engine performance check (including blowby) should be made at mid-test (250 cycles) but it is recommended that engine health checks (e.g. compressions & cylinder leakages) are made at 125 cycle intervals.

Note due to the accelerated thermal cycling aspect of this test the rate at which oil is consumed by the engine may be higher than other durability tests and should be monitored throughout.

4 ENGINE AND TESTBED PREPARATION / INSTALLATION

To understand engine wear characteristics over this test it is advisable to measure key engine components prior to or during engine assembly, and also during or following the post-test engine teardown.

Appendix 1 contains an example list of engine measurements. An updated list of requirements will be developed and finalised through the engine design phases. The test engineer should verify that the required measurements or checks have been made and are satisfactory before proceeding with the test.

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

- 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 fluid leakages using engine build pressure leakage and vacuum decay tests
- Record the final valve clearances
- Record any issues found on build
- Record any modifications or build deviations made during build

It is recommended that all exhaust manifold and turbine flange fixings have their final assembled positions recorded by appropriate (heat resistant) marking (e.g. light scribe marking) so that they may be visually monitored during engine checks for any loosening.

Ensure all parts that require adaption for instrumentation are modified, thoroughly cleaned (and where applicable leak-checked), prior to engine assembly.

It is especially important for this test that the test bed exhaust system should have some flexibility to avoid any undue loads on the turbocharger. The exhaust downpipe attachment and support should simulate the vehicle configuration as closely as possible. Pay special attention to the possibility of thermal expansion / contraction of the test bed exhaust system imparting additional loads onto the Turbo assembly and mounting. Additional expansion joints or similar may be needed to prevent this.

Fluid specifications for this test are:

Fluid	Required Specification	Notes
Fuel	DHPP - A	EN590 or Winter-grade DHPP-A may also be used if specifically requested
Lube Oil	5W50 (Mobil 1 or equiv.)	Renew Oil & filter every 125hrs
Engine coolant	Demineralised water with 2.5% (volume) Servo Anticorr BF corrosion inhibitor (Normal coolant spec.)	40:60 Water/Eth. Glycol mix (Winter spec.) may also be used if specifically requested or if there is a risk concern that erroneous chiller operation may result in freezing.

(Note that in order to maintain better test bed control of the coolant temperature the thermostat is normally modified so that it is fully open for this test.)

The test bed installation should enable inclusion of, and logging from, a blowby meter during the scheduled performance checks. This will likely require the provision of suitable pipework and connections between the engine oil tank breather outlet and the engine vee-mounted air-oil separator.

It is recommended that during GEN1 the blowby meter circuit should also include an upstream oil catch-can type vessel (Min. 2L volume) to prevent the blowby meter from becoming contaminated or overwhelmed with any oil mist or droplets being carried over from the tank.

5 EQUIPMENT AND INSTRUMENTATION REQUIREMENTS

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

Note that in order to avoid an overly long cooling phase and reduce the overall test duration (in hours) it is usually necessary to utilise an external chilled water supply (in addition to the normal test bed recirculation cooling water).

This would normally take the form of a holding tank and external chiller arrangement connected into the test bed cooling circuit via a series of automated valves (see appendix for an example chiller arrangement)

The chiller system must have sufficient volume and cooling capacity to be capable of maintaining the cold-water supply at a target temperature (e.g. 5-10 deg.C) over multiple sequential hot/cold cycles without intervals.

It is recommended that the cooling system set-up for this test includes a non-intrusive flowmeter and sight-glass located in the water outlet pipe from the engine to radiator. This enables continuous monitoring for correct engine coolant flow rate and lack of vapour bubbles which can be compromised if the chiller system and/or various control valves do not function as intended.

For this test, the standard durability test instrumentation shall be fitted to the engine as described in **BE-GEN-001 – Test Cell Set Up** but with additional specific component surface temperature instrumentation as described below :

- This test requires measurement and monitoring of key exhaust system component metal temperatures to ensure that the engine reaches their expected peak in-service temperatures during the test cycle heating phase and are then given sufficient time to cool back to approximate ambient operational levels, during the test cooling phase.
- Therefore, the following additional instrumentation should be added to the engine and the test bed logging system for this test :
  - Exhaust manifold metal temperature(s) – Locations TBA
  - Turbine housing metal temperatures
  - Cylinder head metal temperature – location(s) TBA
- Where possible these should be achieved by welding on exposed-tip thermocouples to the component surfaces, rather than located using machined holes or pockets which can affect the component's thermal stability and robustness (see example shown in Appendix 14.4)
- It is important to consider the placement of any test cell cooling fans to ensure that the surface temperatures are not unduly influenced by variation in air flow (ideally the thermocouples are often situated under production-spec. heatshields)
- Non-intrusive coolant flowmeter (engine outlet – radiator inlet)

5.1 TEST CYCLE CONTROL

Wherever possible the duration of this test cycle's heating and cooling phases should not be fixed but instead determined by the actual time taken to reach the targeted hot and cold component or system temperatures.

This may be achieved in one of two ways:

Fully automated – the peak (hot & cold) control temperatures are continuously monitored and when they have reached a steady-state condition (above or below the appropriate trigger condition) the test sequence automatically progresses to the next test stage.

This is often the most efficient way of robustly running this test for the required number of thermal cycles, but it can sometimes lead to problems if any instrumentation errors or drift occurs. For this reason, it is always recommended that there is an appropriate maximum stage time applied with appropriate error case handling and protection built into the automation system (e.g. flagged to the test operator and/or test suspended) should an instrumentation issue occur.

Trial cycles and regular monitoring – if the automated method described above is not possible or practical then it will be necessary to carry out an initial trial cycle determination phase where multiple heating and cooling phases are run sequentially to determine the mean time taken for the Peak 'Hot' and Min. Cool target temperatures to be achieved (ideally under different ambient and facility cooling efficiency conditions).

Note that this approach may result in a slightly extended test duration in terms of the number of hours required to achieve the required number of thermal cycles.

Also, the test data must be reviewed daily and where appropriate the test phase and stage durations amended to ensure that the engine is not being under- or over-tested e.g. by a slight drop in engine performance or increased test facility cooling efficiency.

6 LOGGING REQUIREMENTS

In addition to logging of the standard durability test instrumentation described in **BE-GEN-001 – Test Cell Set Up** the following parameters should also be logged:

- All additional surface temperature thermocouples applied to the exhaust manifolds and turbine housings (minimum of 4 additional channels) and cylinder head thermocouples (if fitted)
- Any additional thermocouples that may be specifically requested by component suppliers for this test (TBA)
- HT Coolant flow (engine out – radiator in.)

Note: further instrumentation and logging requirements may need to be added as the definitive design phase progresses and any potential risks are highlighted by the FMEA process and ongoing supplier engagement.

See section 9.5 below for the regular parameter logging requirements for this test1 above

Note - It is also recommended that any initial trial set-up cycling, and periodic cycle temperature profile checks carried out through the test, are logged continuously at 1 Hz.

6.1 ECU PARAMETER LOGGING REQUIREMENTS

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

7 TEST SAFETY SHUTDOWN LIMITS

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

Additionally, for this test it is recommended that if the engine is instrumented with individual exhaust port gas temperature thermocouples, or manifold skin temperature thermocouples, the temperature readings from all cylinders are reviewed across the complete cycle and then appropriate low or high temperature alarms and shutdown triggers are set, so that should the readings drift from the norm., any underlying cause may be investigated.

The same approach should also be used for Turbine inlet and/or turbine outlet temperatures.

Note – Exhaust manifold skin temperatures in particular can be very sensitive to the exact location on the manifold (as well as slight underlying differences in combustion temperatures) so preferably the limits should be customised for each cylinder or thermocouple position, following initial running during the BIPO, and then also when 'on cycle'. The temperature shutdown limits will also need to vary with the different stage conditions (i.e. Rated power stage temperatures and degree of normal variation, will be different to High and low idle stages).

It is possible that this approach may lead to some false shutdowns (due to overly tight limits or thermocouple drift or failure, or varying engine boundary conditions such as charge-air temperature or even in-cell cooling fan placement). However, it can be a very useful early warning sign of internal engine wear, deterioration, or combustion-related issues, and will greatly aid understanding if it is a single cylinder that is affected (and which one), or a whole bank. A minor internal engine issue (perhaps only affecting a single cylinder) may deteriorate quickly into a sudden failure of the complete engine. Once this occurs it can often be difficult to determine confidently the root-cause of failure. Hence all shutdown-limit triggered events must be treated with caution and thoroughly investigated (including internal inspection and review of previous test cycle data if required) before the engine is restarted and the test resumes.

It is also recommended that the engine runs with an experienced operator in attendance during the initial engine cycles and also following any shutdown that cannot be traced to instrumentation failure.

8 PRE-TEST ACTIVITIES

If the engine has not run before, a standard BIPO should be performed. Refer to test procedure BE-GEN-002.

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

Measurements *(record in build / logbook)*	• Pre-test crankshaft TV measurement • Cylinder leak down and compression (all cylinders) - see procedure **BE-GEN-003** • Valve clearances post BIPO
Components	• Review if there are any necessary engine rework, component replacement or updates, or additional instrumentation requirements before commencing test. • This test should run with the vehicle specification air filter assembly • A fully jacked-open thermostat may be specified for more reliable test bed temperature control. • The test engineer will advise if any component update requires another performance check to be completed.
Post BIPO Review	• Ensure no abnormal noises at idle • Check for any fluid or gas leaks at idle • Review BIPO data and confirm that engine is signed-off prior to commencing durability test • Check performance test completed to ISO 1585 • Collect used-oil sample from engine post BIPO (100ml)
Oil Requirements	• Engine is to be filled with fresh oil and fitted with new oil filter prior to start of the durability test • Sample of the fresh oil added to be retained (100ml) • New oil weight that is added to engine is to be recorded • Check oil level is correct on dipstick and adjust if necessary o To be performed after engine has idled for 300s and stopped for 600s

Pre-test Checks	• Air path leak check • Installation for fluid and gas leaks ○ Use Swagelok 'snoop' gas leakage detection fluid (or similar) to confirm correct sealing of exhaust system components and absence of any leakage or cracks • Test bed cooling system is fully filled, primed, and bled. Retain 100ml sample of coolant used for fill • Coolant system pressure check at idle for leaks • All instrumentation is responding and reading zero/ambient • Check for correct function of Hot shutdown coolant pump • All necessary instrument and equipment calibrations have been completed (i.e. test cell calibration certificate is current) • Check exhaust back pressure valve function and setting • **Review BIPO data and set appropriate test bed warning or shutdown triggers for manifold and turbine in/out temperatures** • Infra-red thermal image recordings of the whole engine or particular components (e.g. exhaust manifolds and turbochargers) whilst operating at rated power condition and the other test cycle stages. • If external chiller is used check for correct function and test sequence control of all automated valves. Using sight-glass and/or flowmeter data ensure that the engine cooling system coolant supply is not compromised by interruptions in flow or additional aeration especially during and after the chiller system valve operations.
SOT Requirements	• Initiate logger at 10Hz • Switch ignition on and observe correct operation of priming pump and ensure oil pressure in main gallery exceeds 100kPa • Ignition off, stop logger ○ If required oil pressure is not achieved, stop and investigate • If any engine or test cell rework or update activities have taken place following BIPO the carry out a SOT performance test to ISO 1585 • Ensure a minimum of 3 continuous uninterrupted test cycles are logged (Initial trial cycles). Repeat if any cycle sequence modifications are made during the test.

Any issues found on test, or details of component updates post-BIPO should be noted in the testbed logbook and any parts changed retained.

NB. Further requirements may be added as the definitive design and associated analysis, FMEA and DVP activities progress and through ongoing supplier engagement.

9 TEST PROCEDURE

9.1 TEST OVERVIEW

This test cycle is intended to verify the durability of the engine design when cycling between the normal extremes of Hot & Cold engine service usage, and chiefly consists of a heating phase and a cooling phase which are repeated for a total of 500 cycles during the complete test. As stated previously the lengths of the two phases are variable dependant on representative heating / cooling rates and target Hot / Cold cycle temperature limits. However, for guidance the cooling stage may be up to twice as long as the heating phase. This may be accelerated slightly by use of a motoring dyno if available. See sections 9.2 and 9.3 below for further details of the two Heating and Cooling phases.

Transition ramps between steady state running stages are included during which the dyno speed and loading should smoothly transition to the specified conditions.

The ramping stages have been specified over 15 or 30s duration, depending on the speed difference between stages. (Note the ramping stage time is counted as running time at the following test stage condition).

The engine is stopped for the final chilling phase of the test sequence. Engine starting should alternate between electric and air starting. It is recommended that this is programmed into the test sequence for the scheduled engine start/stop events.

Test specification:

Parameter	Unit	Value
Time / Test Cycle (variable)	mins	Approx. 20 – 40
Number of test stages / cycle	-	6
Ramp time between stages	s	15-30
Number of Test Cycles	-	500
Number of scheduled engine starts	-	500
Total Test Time (variable)	hrs	Approx. 166 – 333

Upon first running of this cycle, the 1Hz logged actual cycle temperatures recorded over at least three continuous, uninterrupted repetitions of this cycle, should be reviewed against the intended targets and must be approved as being satisfactory by the responsible test engineer, before continuing with the remaining test cycles. Some initial settling or fluctuation of the temperatures following stage transitions is expected but should be limited as much as practically possible by tuning of the conditioning control system and change of control setpoints during the preceding ramp stage.

Prior to commencing this test, the engine must have satisfactorily completed the BIPO procedure described in **BE-GEN-002**.

The BIPO procedure includes a full load power curve check and additional engine health checks which serve as the baseline durability test start reference condition. However, it is recommended that if the engine or test facility has undergone any significant remedial rework or component updates after completion of the BIPO (including removal and re-installation on the test bed), these checks should be repeated immediately prior to starting this durability test.

Borescope inspections may be specified during the test to align with engine servicing or performance checks, or more frequently if required.

9.2 HEATING PHASE

For the heating phase of the test cycle the engine is operated at rated power condition in order to raise the exhaust system components to their maximum expected in-service temperature (T_{hot}) in the minimum amount of time.

During this phase the target test bed cooling system temperature setpoint should also be set to the max. simulation coolant temp. -2 deg. C (to allow for some drift/overshoot) *[i.e., current simulation data shows 122 deg. C at HT radiator inlet at Rated power condition in 55 deg. C ambient, so the testbed coolant control should be set to 120]*

Note that it is likely that the coolant temperature will stabilise before the exhaust component temperatures stabilise or reach their max. test temperature. If this is the case the coolant temperature setpoint should be adjusted to ensure that it remains just below (e.g. -2 deg. C) any high coolant temperature derate protection function activated by the calibration.

9.3 COOLING PHASE

Once the stabilised hot temperature target has been achieved the test cycle should dwell at this condition (for 30s) before commencing the cooling phase.

Initially a short, fixed duration, high speed / low load condition (e.g. High Idle) stage is run which ensures a high and even flow of relatively cooling air through the exhaust system, followed by a ramp down to idle.

Simultaneously the target test bed cooling system setpoint should initially be reduced to a low ambient (but warmed engine) condition *[i.e., Current simulation data shows 91 deg. C at HT radiator inlet at Rated power condition in a 25 deg. C ambient, therefore a setpoint of 85 deg. C is considered appropriate for the light load stage].* This results in initial cooling from the normal test bed recirc. water cooling only and ensures that the cooling rate is not too extreme (as this can often result in distortion issues not representative of in-service operation).

Directed spot cooling or air movers must not be used on the exhaust system during the initial cooling stages as this can result in artificial thermal stresses due to uneven cooling.

Finally, once the engine cooling system and exhaust system component temperatures have dropped to appropriate levels the engine is stopped and the final cooling stage initiated. This uses the lower temperature chilled water circuit to bring the engine temperatures down to the required cold start target [TBA] before the next cycle commences.

9.4 TEST CYCLE SEQUENCE

The test cycle stage sequence is as defined in Table 1 below:

STAGE No.	STAGE NAME	STAGE TIME (Mins)	TOTAL TIME (mins)	DYNO. SPEED (rpm)	ENGINE LOAD (%)	TARGET $T_{HT\ Coolant}$ SETPOINT (°C)	TARGET $T_{LT\ CoolerOut}$ SETPOINT (°C)
1	**Start/Idle**	**0.75**	**0.75**	**830**	**0**	30	30
	Ramp	0.5	1.25	2600	100	120	75
2	**Rated Power**	**(5.5)**	**(6.75)**	**2600**	**100**	120	75
	Ramp	0.25	(7)	2860	Min.	85	30
3	**High Idle**	**0.5**	**(7.5)**	**2860**	**Min.**	85	30
	Ramp	0.5	(8)	830	0	40	30
4	**Hot Idle**	**(5)**	**(13)**	**830**	**0**	40	30
5	**Warm Idle**	**(5)**	**(18)**	**830**	**0**	30	30
6	**Stop/Chill**	**(4)**	**(22)**	**0**	**0**	10	30

TABLE 1 - TEST CYCLE STAGES

Note the stage & total cycle times in brackets are examples only as the durations of stages 2, 4, 5 & 6 are controlled by the achievable engine heating/cooling rates. Also, the coolant setpoints stated are for guidance only and will need confirmation & possible modification following initial test bed running.

The objectives and required durations of stages 2, 3, 4, 5 and 6 are as follows :

Stage 2 :– Maintains rated power condition until $\mathbf{T_{hot}}$ (peak exhaust system temperature target) is achieved. Note that due to the abrupt change it may be necessary to set the coolant temperature setpoint slightly lower to avoid a high temperature overshoot.

Stage 3 :– An initial short, fixed duration, stage at high speed / min. load in order to commence rapid but even cooling of the exhaust system components from internal exhaust flow. The HT coolant temperature setpoint is also reduced to increase coolant heat rejection.

Stage 4 :– Increased engine cooling achieved by further reduction of the recirc-water coolant temperature setpoint. No chilled water usage is allowed during this phase to ensure the temperature gradient is not too large (must not exceed heating thermal gradient). Cell extract fans may be switched to enable max ambient cooling but do not activate any ‘spot’ or localised coolers or air blowers.

Stage 5 :– Once the engine water outlet temperature has dropped below an agreed threshold ($\mathbf{T_{cool}}$ e.g. 60 deg. C) and the exhaust system surface temperatures fall below 200 deg. C the coolant temp. control setpoint should be reduced further and exhaust fans or air movers may be activated.

Stage 6 : – Once the engine water outlet temperature reaches a further threshold ($\mathbf{T_{stop}}$ e.g. 45 deg. C) the engine should be stopped and the chiller system control valves may be opened fully to maximise cooling until the target $\mathbf{T_{cold}}$ temperature is achieved. Exhaust fans should remain on during this stage.

The test cycle speed / load stage conditions and typical examples of coolant and exhaust metal temperature profiles are shown in graphical form in Figure 1, Figure 2 and Figure 3 below :

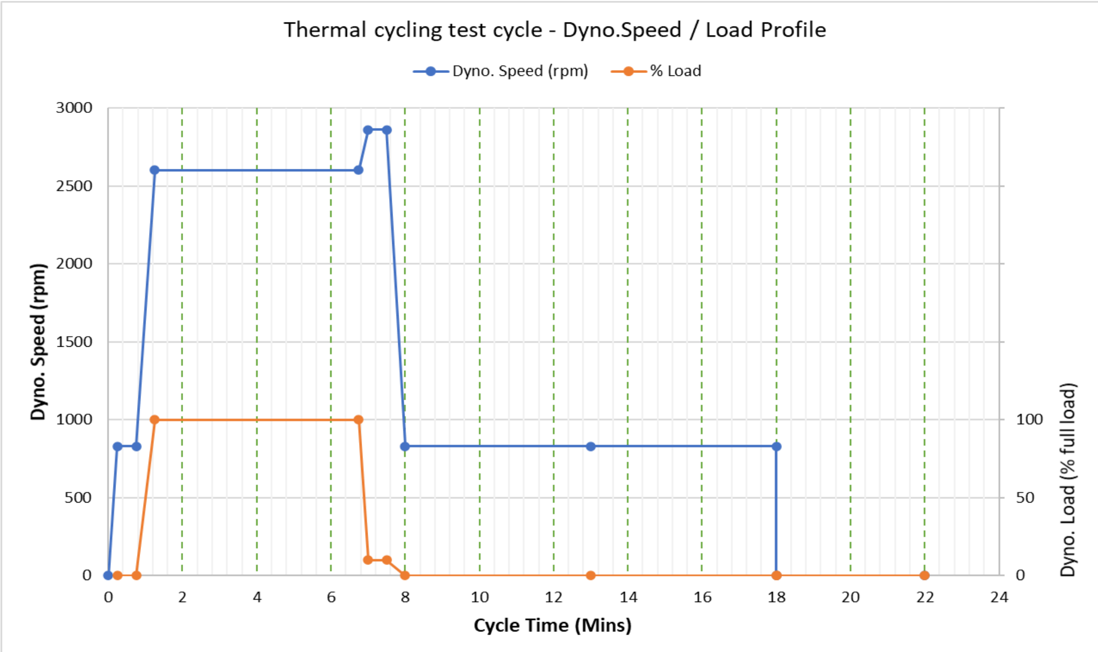

FIGURE 1 - TEST CYCLE DYNO SPEED AND LOAD PROFILE

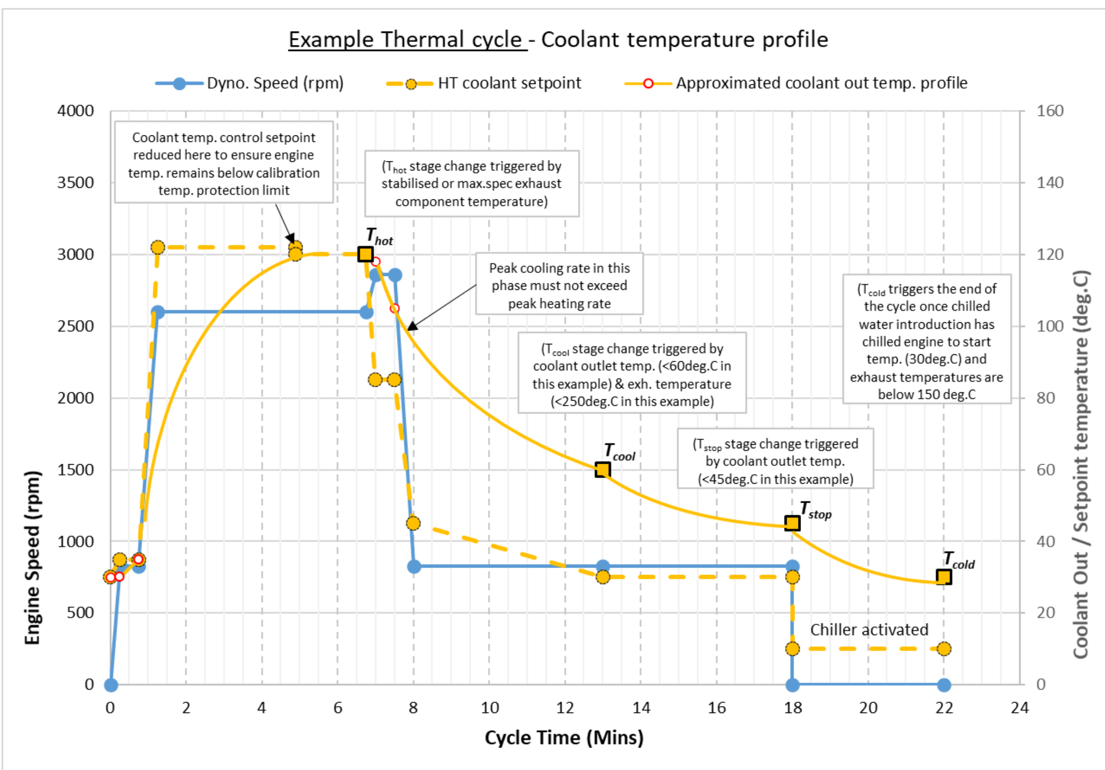

FIGURE 2 - EXAMPLE ENGINE HT COOLANT TEMPERATURE PROFILE AND STAGE TRANSITION POINTS

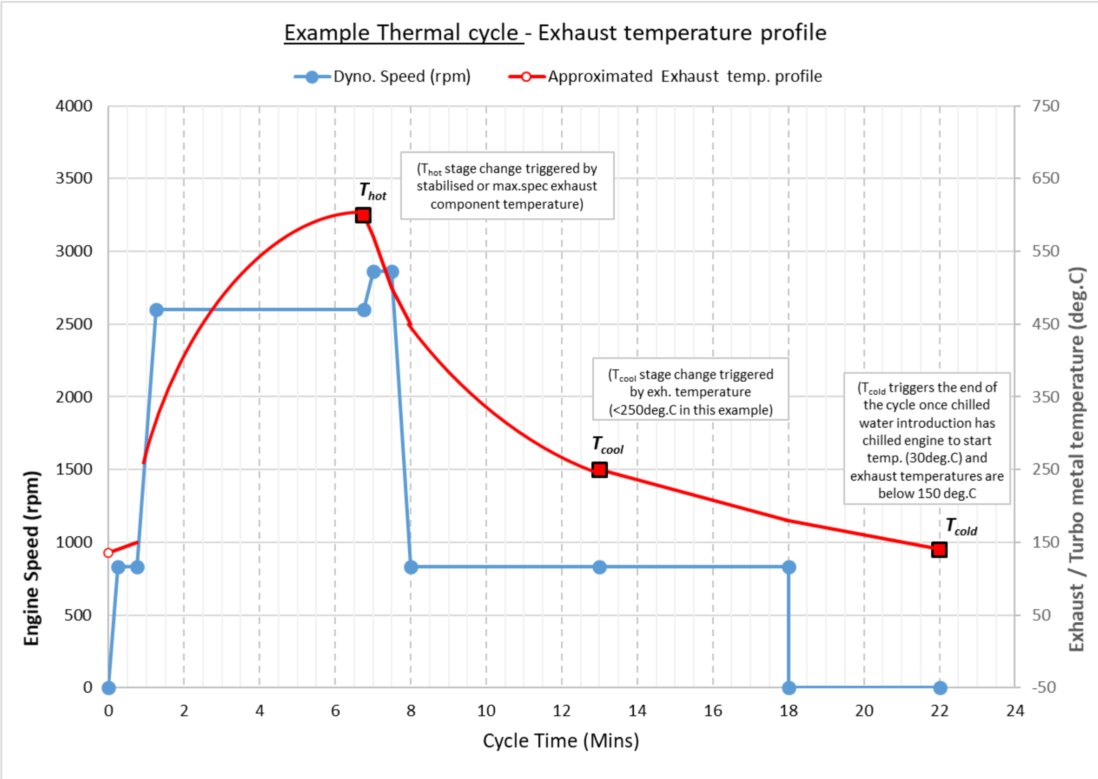

FIGURE 3 - EXAMPLE ENGINE EXHAUST SURAFCE TEMPERATURE PROFILE AND STAGE TRANSITION POINTS

Note that initial target temperature values for the cycle control parameters $\mathbf{T_{hot}}$, $\mathbf{T_{cool}}$, $\mathbf{T_{stop}}$ and $\mathbf{T_{cold}}$ will be developed during the definitive design phase following further design, analysis and simulation activities and interaction with the relevant component suppliers. The example values listed herein may be used as a general guide for planning purposes.

9.5 TEST PARAMETER LOGGING

For engine condition monitoring and verification of correct test control, averaged logs of all the engine and test facility parameters stipulated in section 6 above, should be recorded at fixed points through the engine test cycle, (hereafter referred to as KP (key point) logs).

This enables easier ongoing engine health and trend monitoring analysis to be performed, by cross plotting the same test condition from each test cycle throughout the test (see example in Figure 5 in section 10.1 below).

KP logs should be automatically initiated by the test bed control and automation system (for repeatability) towards the end of each of the six test stages and should be averaged over a 30-second steady-state running period (where possible)

The recommended cycle timings for initiation of the 30s averaging periods for the key points logs, are shown in Figure 4 below, aligned with 30-35secs preceding the end of each test stage.

Additionally, it is recommended that the complete test duration is logged continuously at 1Hz so that in case of an engine durability, functional or performance issue, regular cycle data from preceding cycles may be examined and analysed to determine the possible onset of the issue and assist in the determination of the root cause.

Graphical representation of the distribution of Key point logs throughout the test cycle :

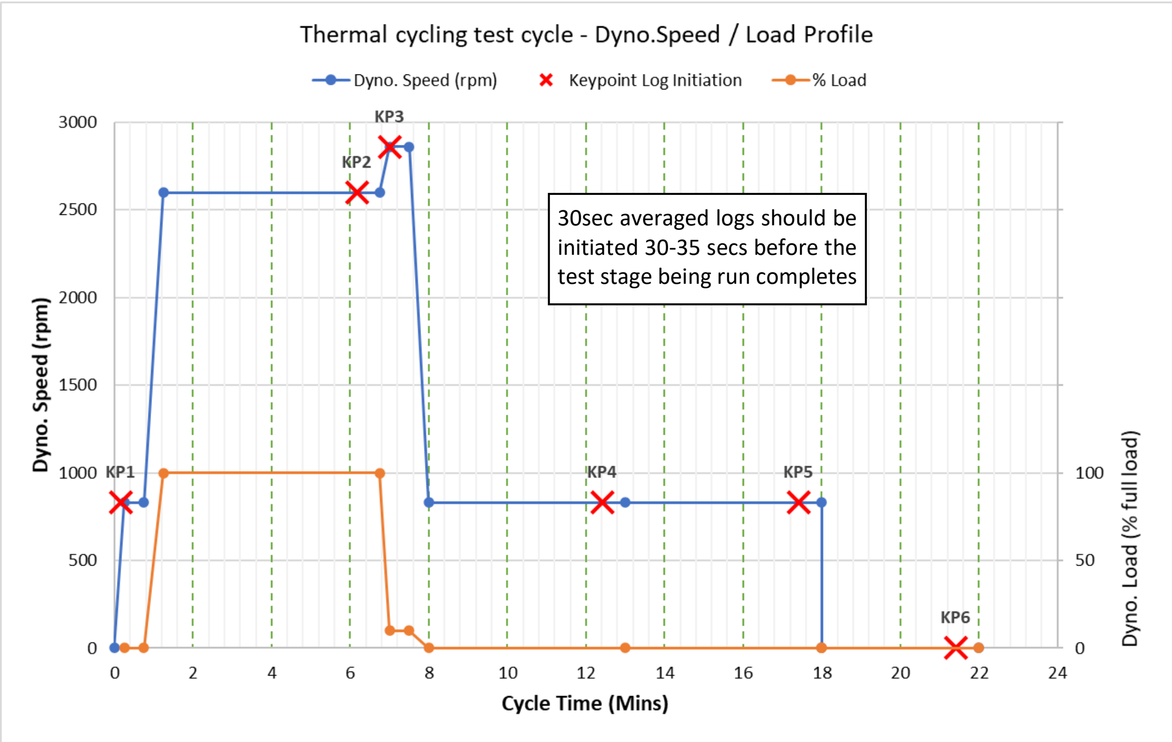

FIGURE 4 - TIMING OF KEY POINT LOG 30-SECOND AVERAGING INITIATION

9.6 TARGET TEST STAGE FLUID TEMPERATURES

This test requires variation of the engine coolant (HT & LT) fluid temperatures over the cycle, to defined target temperatures for each test stage (see 9.4 above for the targets).

For the purposes of regulating the engine test temperatures to achieve these targets, the following instrumentation measurement positions and control methods should be used:

- Coolant (HT & LT)
    - HT Temperature measured at the Engine coolant outlet to test bed HT cooler (close to engine).
    - LT Temperature measured at the LT coolant radiator outlet (TBC)
    - Engine HT & LT coolant temperatures to be regulated to control setpoints by the temperature & flow of test facility cooling water through the test bed HT & LT heat exchangers.

(Note in order to assist temperature control the engine thermostat may be replace with a fully jacked-open version for this test)

During the durability testing it is not intended to control the oil and charge air temperatures directly, but instead they will be allowed to fluctuate depending on the engine power setting and the HT and LT cooling systems temperatures.

- Oil
  - Oil temperature is not directly controlled but may be regulated by the temperature & flow of test facility cooling water through the test bed LT heat exchanger (influencing engine oil cooler heat rejection). The oil temperature must not be allowed to rise above 135 °C at any point during this test.
- Charge Air
  - Temperature to be measured from the intake manifold plenum (similar position on each bank, to be specified)
  - Charge air temperature is not directly controlled but may be regulated by the temperature & flow of test facility cooling water through the test bed LT & HT heat exchangers (influencing the engine charge air cooler heat rejection).

The allowable tolerance for the temperature targets is ± 5 °C except for the peak temperatures which should not be exceeded but may be up to 10 °C lower than those stated, i.e.

Fluid	Measurement location	General temperature control tolerance (°C)	Allowable peak temperature (°C)
HT Coolant	Engine coolant outlet	± 2	125 (TBC)
LT Coolant	LT Radiator outlet	± 2	TBA
Oil	Oil gallery	± 5	135
Charge Air*	Intake manifold plenum (x2)	± 2	TBA

*Note: The Tender document states *"Limited natural power reduction is permitted at higher temperatures of charge air"*. However, to ensure the robustness of this test the charge air temperature should be maintained at a suitable temperature during the Hot rated power stage so that engine performance is <u>not</u> significantly adversely affected.

The actual expected range of values for these parameters will be confirmed during the DD phase and this procedure will be updated accordingly.

It is recommended that appropriate test bed parameter warning thresholds are set to flag any test stage operation where these control requirements are within ± 1 °C of not being met, so that appropriate control setpoint adjustments may be made.

Some variation and fluctuation of the temperatures can be expected to occur at the start of stages following the ramp transitions. Wherever possible this period of fluctuation should be reduced (by appropriate adjustment of control setpoints during the preceding ramp stage) and stabilisation time limited to the first 2 mins. of the test stage.

Note that for the ramping transition stages the test bed control setpoints may need to be different for each ramp in order to maintain the targets required.

Other test bed control set points should be initially set as follows:

Parameter	Unit	Initial Target	Allowable range
Fuel Temperature (LPFP in.)	°C	40 +/- 5	30 - 70
Air Intake Temperature	°C	30 +/- 5	20 - 40
Oil Level	Initial Max fill with Top-up to Max. approx. every 10hrs of running or if below min. level. Record and monitor all additions and drain weights		

Adjustment of these test bed temperature control parameters may be necessary in various test stages to ensure the actual engine operating conditions remain within their specified limits.

9.7 Engine Warm-Up

As this test cycle starts from a cold engine condition no preparatory warm-up is required before commencing cycling. However, in case of an aborted test or unscheduled stop refer to section 9.9 below for how to resume the test cycle.

9.8 Scheduled Engine Stops

The engine should be stopped after every 25 cycles (≈10 hrs) for a minimum of 5 mins, or longer time if required to perform any necessary scheduled or unscheduled in-cell inspection, servicing, or maintenance activities (if longer). Note that this activity may take place during the final engine stop & chill stage as long as appropriate risk assessment is carried out (e.g. consideration of prevention of auto- engine restart, chilling system failure etc.) and it is deemed safe to do so.

Upon restarting the engine should commence the thermal cycle at the first stage – no warm-up sequence is required or should take place.

Longer stop periods and engine cooldown are expected to occur at least every 125 cycles when the engine will have its oil and filters changed and undergo a performance test as well as other measurement activities.

The test data from these performance test and other engine monitoring measurements must be thoroughly reviewed and approval given before proceeding with the test. A recommended test monitoring and servicing regime is described in Appendix 14.2

9.9 Unscheduled Stops

If an unscheduled engine stop occurs (either by manual or automatic test bed shutdown) the causes of the shutdown must be investigated thoroughly before proceeding.

In cases where the shutdown is unexpected the post-mortem shutdown log must be reviewed, and the cause identified. The test engineer should be notified, and the test may only resume once the engine heath has been confirmed by turning the engine over by hand (minimum) and possibly following further external & internal engine examination.

The shutdown must be logged in the test logbook, together with details of the checks made and any observation or conclusions. Ensure the post-mortem data is archived.

The test stage in which the unscheduled stop occurred, must be repeated. Depending on the stage at which the test cycle was terminated, and the current engine temperature proceed with the test cycle as follows:

Aborted stage	**When Coolant Temperature is -**		
	<50 deg. C	**>50 and <80**	**>80**
Heating phase (Stages 1 & 2)	Resume test from stage 1 Idle	Resume test from stage 1 Idle	Resume test from stage 1 Idle
High Idle (Stage 3)	Resume test from Stage 4	Resume test from Stage 4	Resume test from Stage 4
Cooling phase (Stages 4 & 5)	Resume test from Stage 5	Resume test from Stage 4	Resume test from Stage 4
Stopped / Chilling phase (stage 6)	Resume Stage 6	Re-run from Stage 5	N/A

It is recommended that the engine runs with an operator in attendance upon resuming the test sequence, until the engine health and appropriate setting of the test bed automatic shutdown trigger values are satisfied.

Engine restarts required as a result of any unscheduled engine stops should initially be made using the electric starter (once appropriate action depending on the nature of the engine stop has been taken).

10 MONITORING, SERVICING AND REPORTING REQUIREMENTS

10.1 Monitoring and Servicing Regime

During durability testing it is important that all necessary engine & test cell monitoring and servicing requirements are actioned in a timely and organised manner. Also, to maximise the test efficiency, wherever possible the actions required should be aligned with the end of a test cycle, not during the cycle.

The cycle key point (KP) data logs are to be routinely plotted against test time to monitor the performance trend of the various engine parameters (see Figure 5 examples below) :

For this test the oil and oil filter should be replaced every 250 cycles or 125hrs (max.) unless otherwise specified by the test engineer.

It is also important that oil quality is monitored throughout this test by rapid oil lab. analysis. This will enable any need for more (or less) frequent oil servicing to be identified, and provide insight into ongoing engine wear, damage, or oil-ageing related issues.

The ongoing oil consumption rate determined from the frequency and quantity of oil top-ups and oil renewal fill & drain amounts, must be continuously reviewed. Any sudden worsening of consumption rate should be alerted to the test engineer and further investigative tasks may be necessary.

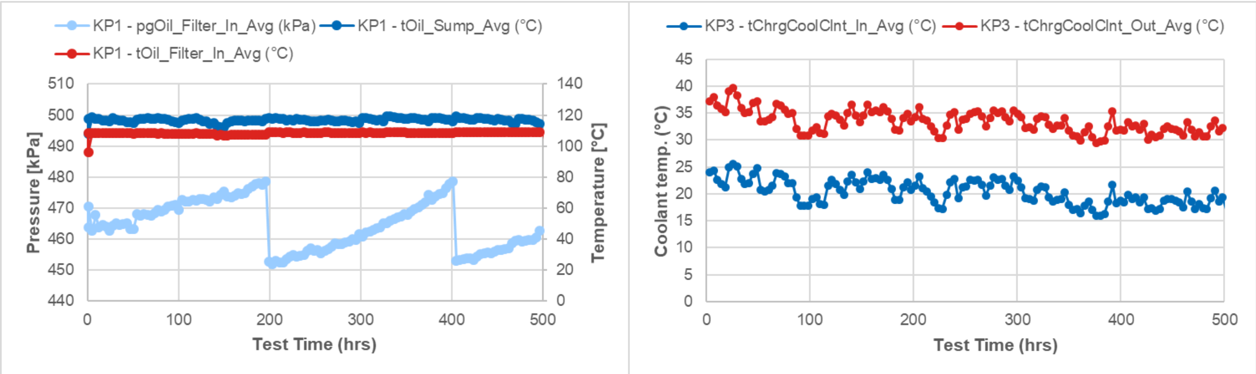

FIGURE 5 - EXAMPLE OF TEST TREND PLOTS

Similarly, any regular ongoing cooling fluid consumption must be investigated, and results of regular engine leak detection inspections should be noted and monitored.

At the test mid-point (250 cycles) a scheduled engine performance test should be carried out and the logged data cross plotted with the start of test results and reported.

An initial draft of the specific monitoring and servicing tasks required for this test are shown in Appendix 14.2. In order to ensure that all the required tasks take place at the necessary time, and to ensure clarity for the test bed operators, it is recommended that this regime, is adopted and programmed into the test bed control system.

However, please note that this schedule may need revising or additional requirements adding, as the definitive design and associated analysis, simulation, FMEA and other DVP activities progress, or based on observations made from any preceding GEN1 functional and durability testing.

10.2 Reporting

The BE1500 project engineering team should be advised by a daily email of the number of test cycles and hours achieved by the test engine in the previous 24hr period, together with a summary of results or observations from any servicing or monitoring tasks, and any such items planned over the forthcoming 24hr period.

Also, it is recommended that all of the key-point trend plots (see Figure 5 examples above) are updated and reviewed so that any concerns with changing parameter trends may be reported. If any concerns are observed these should first be reviewed by the responsible test engineer in case any intervention, or further inspection or remedial action is required.

Less frequently, at a frequency to be agreed (e.g. aligned with engine scheduled checks – see Appendix 14.2 Recommended Test Monitoring Regime), a more thorough delivery of information will be required, including (but not limited to):

- Latest performance check data (cross-plotted with previous performance results)
- Engine blowby and crankcase pressure data
- Oil consumption trend data
- Oil sample analysis data and plots
- Summary of any service or engine monitoring measurements
- Summary of any component replacements since the preceding review

11 POST-TEST ACTIVITIES

Once the test has been completed, the following tasks are to be completed:

EOT Requirements	• Perform EOT Power curve (with 30s averaged logs at each stabilised speed/load condition and 1Hz logging throughout)
	  ○ Crankcase blow-by is to be logged during this check
	• Take Infra-red thermal image recordings of the whole engine or particular components (e.g. exhaust manifolds and turbochargers) whilst operating at rated power condition and the other test cycle stages.
	• Inspect for and log any visible fluid or gas leakages
	• Use 'snoop' gas leakage fluid to check for presence of cracks or poor of exhaust system components
	  ○ Photograph and record in logbook

Oil Requirements	• Retain 100ml oil sample from the oil tank, ensure 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
Other Measurements *(record in build / logbook)*	• Post-test crankshaft TV performance • Cylinder leak down and compression on all cylinders - see procedure **BE-GEN-003** • Valve clearances (optional, if requested)
Checks	• Ensure Engine logbook is complete and up to date • Any parts removed from engine during test must be clearly labelled with the engine no., removal date, engine hrs and position on engine (if relevant) • Ensure all test data is suitably archived • All open engine ports or interfaces must be plugged or suitably protected from dust / debris ingress

The test engineer and engineering project team should review the data before engine is removed from the testbed for disassembly.

12 TEARDOWN ACTIVITIES

The engine is to be torn down post-test and fully inspected to determine the amount of wear that has occurred on the various engine components. The requirements and instructions for this will be provided in a dyno. test engine teardown procedure.

Typically, during the teardown, the following activities will need to be completed:

- Inspect engine condition when on stand prior to any part removal and photograph
- Valve clearance measurement and record values
- Measure and record the break-away and back-to-mark torque values of critical fasteners
- Measure and record the vacuum achieved for intake and exhaust ports in cylinder head with valves installed
- Ensure engineer is present during teardown to photograph and catalogue any issues and record the general condition as found at the end of test before any components are disturbed.
- Components must not be cleaned unless specifically instructed

On dis-assembly key components will need to be examined, measured, and photographed, typical examples for consideration are listed below. The inspection requirements for this specific test will be included in the teardown procedure.

- Cylinder block (cylinder liners and main bearing bore)
- Cylinder heads
- Head gaskets
- Pistons
- Piston rings
- Main and big end bearings
- Crankshaft
- Conrod little end bush
- Gudgeon pin
- Camshafts
- Valves
- Turbochargers (Visual & supplier inspection)
- Exhaust manifolds (Check for flange flatness & cracking)
- Intake manifolds (Check for flange flatness & cracking)
- FIE Turbochargers (Visual & supplier inspection)
- Front and rear geartrain components
- Water pump (Visual & supplier inspection)
- Oil pump (Visual & supplier inspection)

Condition of these components shall be documented in a report pack with all required measurement results and relevant photographs.

13 PASS / FAIL CRITERIA

Principally, this test will be considered to be a pass if the engine is still functioning correctly at the end of the 500 cycles.

However, the following criteria should also be met

- EOT engine performance is with ±5% of SOT performance
- No key component failures (i.e. meets critical functions at end of test)
- No significant fluid or gas leakages (especially exhaust system components)
- Rate of oil degradation is acceptable for amount of time used
- Oil consumption is within technical specification targets (to be advised)
- Blow by is within technical specification targets (to be advised)
- No significant wear of the cylinder system, crank train, valvetrain, geartrain, intake or exhaust system that may be considered close to failure
- No excessive depositing within the cylinder system, intake or exhaust system that can significantly affect engine function

NB. These criteria may be further revised or added to as the definitive design and associated FMEA activities progress and ongoing supplier engagement.

14 APPENDIX

14.1 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].*

14.2 Recommended Test Monitoring Regime

Action	Every 25 cycles (≈10hrs)	Every 50 cycles (≈20hrs)	Every 125 cycles (≈50hrs)	Every 250 cycles (≈100hrs)
5-minute engine stop (minimum)	Yes	Yes	Yes	Yes
Visual safety check of engine & test cell	Yes	Yes	Yes	Yes
Check oil level and top-up to Max. (record amount of any oil added)	Yes*	Yes	Yes	Yes
Visual engine leak check (record observations in logbook)		Yes	Yes	Yes
Check intake system fluid drains & empty		Yes*	Yes	Yes
Weigh & empty CCV catch cans (if fitted)		Yes*	Yes	Yes
Update and review key-point trend graphs		Yes	Yes	Yes
Take & retain 100ml used oil sample (replace with fresh oil)		Yes	Yes	Yes
Perform engine leak-down and compression checks			Yes	Yes
Perform other monitoring measurements e.g. valve clearances, Crank TV measurement etc.(TBA)			Yes (TBC)	Yes
Carry out engine performance test				Yes
Oil and filter change				Yes*
Review all data before proceeding with test			Yes	Yes

* - More frequently if necessary
(Intervals given in hours are for guidance only – preference is to use cycle count for scheduling of activities)

Note that this schedule may need revising or additional requirements added, as the definitive design and associated analysis, FMEA & DVP activities progress, or based on observations made from any preceding GEN1 functional and durability testing.

14.3 EXAMPLE COOLING SYSTEM ARRANGEMENT WITH EXTERNAL CHILLER

System has 3 modes of operation:

Warm up

Valve b open (i.e. using hot circuit only). Valve a open for left-right flow only. All other valves closed. Engine temperature as achieved

Maintain Temperature

Used for running at steady temperature. Valves b, e & d open. All other valves closed. 3 way valve (a) controlled to moderate flow to achieve desired temperature

Chill Down

Valves a, e, g & h open (i.e. cold circuit). All other valves closed. Chiller pump turned on. Temperature as achieved using chiller rig and buffer tank

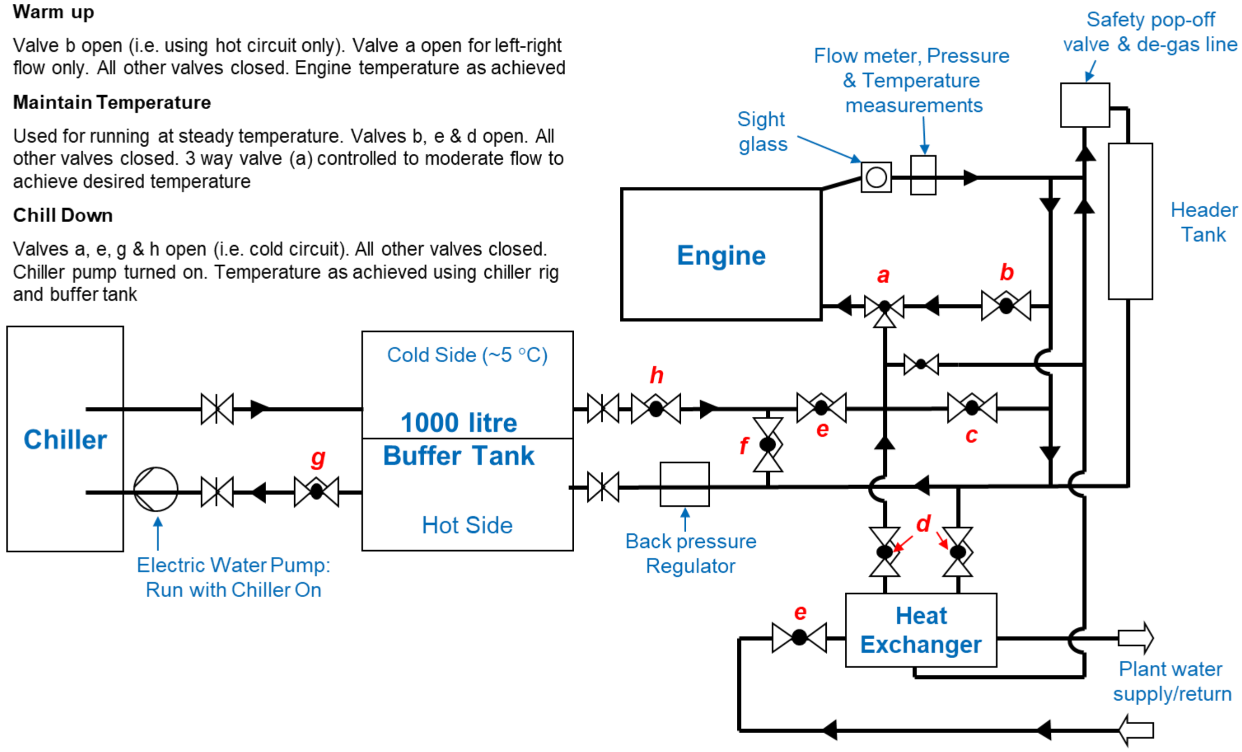

FIGURE 6 - EXAMPLE OF SLIGHT GLASS USED TO MONITOR FOR AIR IN COOLANT

14.4 Example Of Exhaust Manifold Surface Temperature Instrumentation

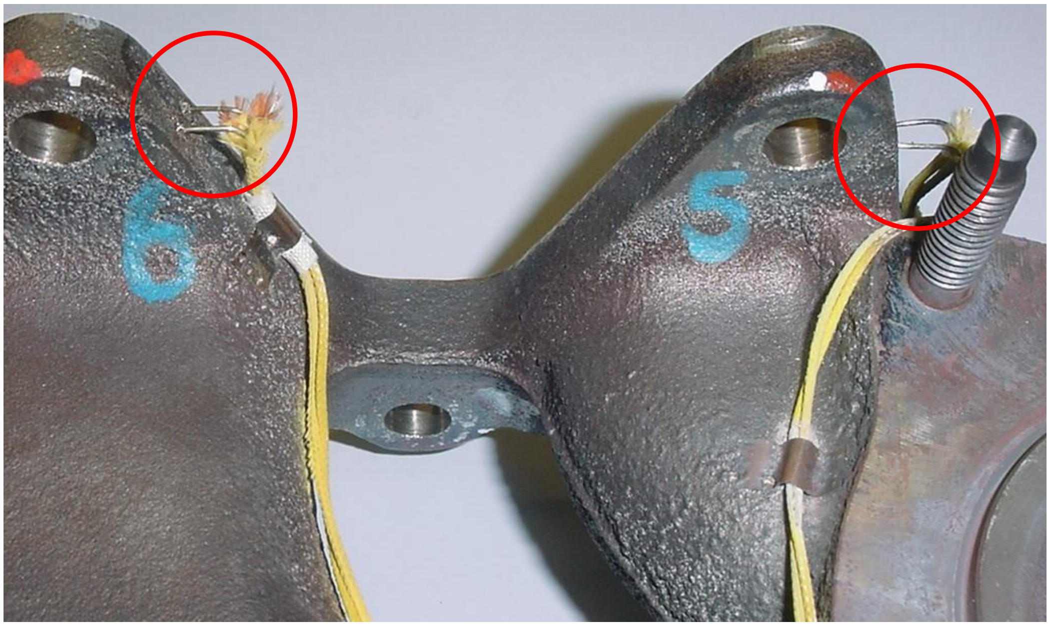

FIGURE 7 - EXHAUST MANIFOLD WITH SURFACE TEMPERATURE INSTUMENTATION ON HEAD MOUNTING FLANGES

FIGURE 8 – CAPACITIVE-DISCHARGE THERMOCOUPLE ATTACHMENT UNIT (TAU) USED FOR WELDING TYPE K THERMOCOUPLE WIRE DIRECTLY TO COMPONENT SURFACE

15 REVISION HISTORY

Issue	Date	Description
01	14th Sept. 2021	Initial Release