400HR ACCELERATED DURABILITY

Test No.	BE-DUR-003	Engine Variant	GEN1	Issue level & Date	Issue 01 16 June 2021

1 TEST OVERVIEW

The aim of the 400hr Accelerated durability test is to verify the durability and robustness of the complete engine assembly and principally the core '5 C's' major components (Con-rod, Cylinder Block, Cylinder Head, Crankshaft, camshaft) and the piston assembly.

A specific 2hr repeating test cycle has been formulated so that the critical engine components are subjected to as many peak-load or highly stressed cycles as possible within the 400hr duration.

The test cycle content has been developed with the consideration that this is expected to be the first of the suite of durability tests to be run, and is intended to provide good confidence of the base engine function and durability, whilst operating at the peak engine loads and speeds for extended periods.

The number of different test conditions included has been minimised so that the time required to develop a robust and representative full-load calibration for this test may be shortened.

2 GENERAL DETAILS

This test consists of a 2 hour, 26-stage cycle, repeated 200 times, and consists of :

- 33% duration at rated power condition (10 million firing cycles)
- 8% duration at continuous overspeed condition (5 million engine revs.)
- 20% duration at peak torque condition (10 million engine revs.)
- 18% duration running slow full-load ramping stages around peak torque condition (1560 – 1800rpm)
- 5% at rated speed, unloaded (3 million engine revs.)
- Total of 76% of the test is at full engine load
- 8% duration at Idle speed (5% at loaded idle condition)
- 25% of the test duration is with elevated fluid temperatures representing in-spec. hot ambient operation
- 100 scheduled normal engine starts and brief stops
- 30s transition ramps between stages

(See section 8.2 below for a full breakdown of cycle content and stage sequence)

Also,

- Oil & filter servicing is initially recommended every 100hrs due to the amount of high power and speed content. Pending results of the planned ongoing sample analysis, the service interval may be able to be extended.
- Engine performance check (including blowby) every 100hrs

The primary objectives of this test are:

- Determine the robustness and reliability of principally the core 5C engine components and related systems such as the Piston Assembly, FIE and Turbos.
    - In turn, validate analysis that has been used to design the engine
- Determine engine performance stability and degradation over time
    - Understand what components may be wearing that are contributing to this degradation
- Determine engine key functional performance stability and if it degrades over time
    - i.e. lubrication system, crank train, coolant system etc
- Assess the rate at which oil is consumed by the engine during severe usage (atypical of service operation), and aid in the validation of oil and oil filter service intervals
- Assess system and component service life and overhaul requirements

3 ENGINE AND TESTBED PREPARATION / INSTALLATION

To understand engine wear characteristics, 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 definitive design phase. The test engineer should verify 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

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

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 100hrs
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

4 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.

For this test, only the standard durability test instrumentation shall be fitted to the engine as described in **BE-GEN-001 – Test Cell Set Up**.

Performance rating to be carried out as per ISO 1585 (accuracy & accessories).

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 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:

- Ongoing incremental counts of the instances and duration of hot shutdown pump activation
- Ongoing incremental counts of the instances and duration of electrical motor crank attempts
- Ongoing incremental counts of the instances and duration of air starter crank attempts

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.

5.1 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.

However as this is likely to be the first durability test to be undertaken it is possible that a minor amount of additional ECU parameter logging may be requested for this test, to verify correct function of the engine calibration throughout. This will be advised during the calibration development testing.

6 TEST SAFETY SHUTDOWN LIMITS

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

Additionally 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.

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 the limits should be customised for each cylinder position following initial running during the BIPO, and then when 'on cycle'. The temperature limits will need to vary with the different stage conditions (i.e. Rated power stage temperatures and normal variation, will be different to Peak Torque).

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.

Due to the amount of high load and overspeed content in this cycle it is likely that 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 following any shutdown that cannot be traced to instrumentation failure.

7 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 required before commencing test. • This test should run with a new 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 • 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 may also be requested
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 o 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

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 maybe added as the definitive design and associated FMEA activities progress

8 TEST PROCEDURE

8.1 TEST OVERVIEW

This test is intended to provide an initial early level of confidence in the durability and reliability of the engine design operating over a multi-stage repeating 2hr cycle for a total test duration of 400hrs. The test cycle conditions, and durations have been selected principally in order to exercise the core engine components (5C+) to their expected peak load cases, for verification of their robustness to fatigue, overload or associated wear. The duration of the peak power and peak torque stages has been calculated to accumulate 10 million firing, and engine rotation cycles respectively, to verify engine fatigue robustness at these conditions. This type of accelerated test is considered more aggressive than the Duty & Drive cycle durability tests and not typical of normal service usage.

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 as 30s duration but maybe shortened to 20s if the dyno control setup allows. (Note the ramping stage time is counted as running time at the following test stage condition).

Test specification:

Parameter	Unit	Value
Time / Test Cycle	mins	120
Number of test stages / cycle	-	26
Ramp time between stages	s	20-30
Number of Test Cycles	-	200
Total Test Time	hrs	400

The cycle also includes controlled variation in fluid temperatures, representing both normal ambient operating conditions and operation in a hot ambient.

It is intended that the target hot ambient coolant and oil temperatures required are achieved by control of the test bed cooling system heat rejection, rather than through the addition of potentially intrusive and disruptive test bed conditioning (cooling & heating) systems.

Upon first running of this cycle, the 1Hz logged actual cycle temperatures recorded over at least two 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. The test bed temperature control set points should be adjusted to ensure the actual temperature conditions required for each stage are achieved over at least 85% of the stage duration.

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.

Also, if this is the first durability test taking place on the test bed it is recommended that the engine has an internal borescope inspection of all cylinders. Further borescope inspections may be specified during the test to align with engine servicing or performance checks, or more frequently if required.

8.2 TEST CYCLE SPEED/LOAD CONTENT

The accelerated durability test cycle is made up of phases of running at a small number of critical engine operating conditions as summarised below:

Condition	Engine Speed (rpm)	Engine Load (%)	Total time /cycle (mins)	%age of total test duration	Duration Notes
Rated speed	2600	100	40	33%	>10e6 firing cycles
Peak torque speed	1560	100	23.5	20%	>7e6 crank cycles
Peak torque speed, min. load	1560	20	9.5	8%	3e6 crank cycles
Continuous overspeed	2860	*Min.	9.5	8%	>5e6 crank cycles
Rated speed (unloaded)	2600	*Min.	6	5%	3e6 crank cycles
****Peak crank / bearing loads**	1560 - 1800	100	22	18%	2 min. duration speed ramps through peak load range
Loaded Idle	830 (TBA)	100	6	5%	Generator / Compressor loading may be required (TBA)
Min. Idle	TBA	0	3.5	3%	
		Total:	**120**	**100%**	

*Min. load is lowest load to maintain satisfactory dyno. speed control

**This condition is a slow full-load engine speed ramp (2 / 3 mins) between 1560 – 1800rpm not steady state

Note also that the speeds for min. idle and loaded idle are not confirmed but will be advised later.

The engine should be stopped after every 4 cycles (8 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).

Upon restarting the engine should undergo a programmed and logged, warm-up sequence as described in section 8.6 below, until the coolant temperature conditions for stage 1 are met. This running time must not be counted as test-time.

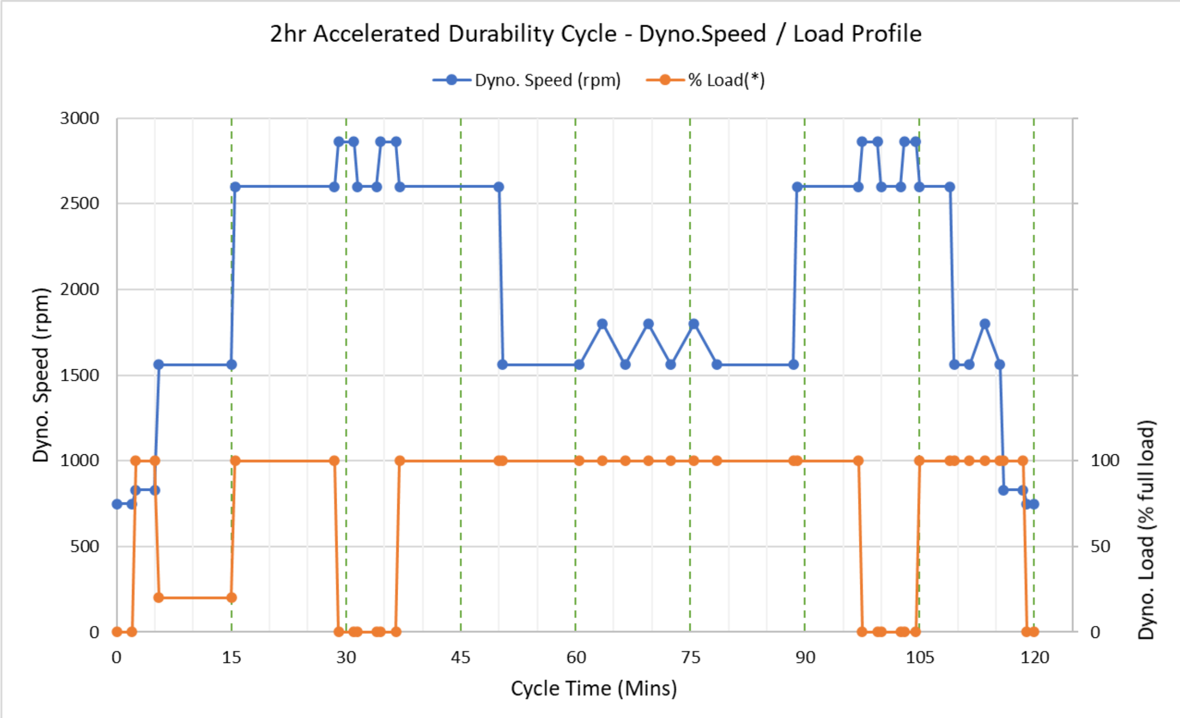
8.3 TEST CYCLE SEQUENCE

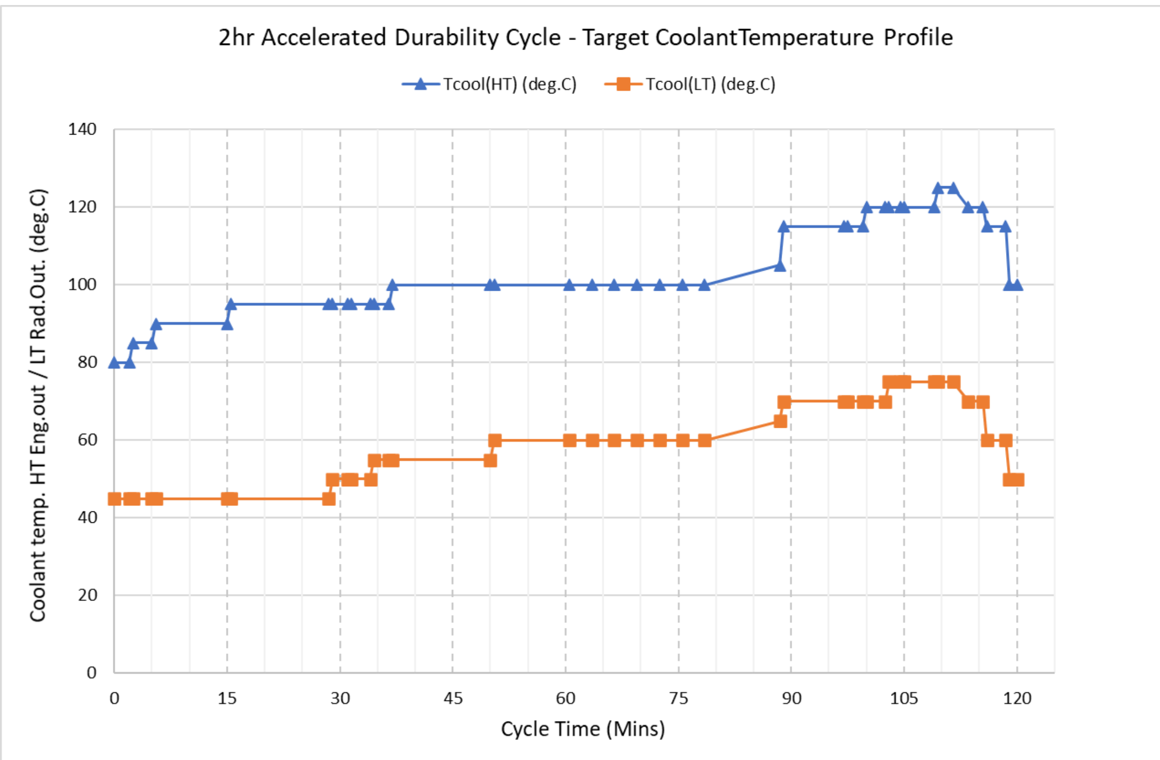
The test cycle stage sequence is defined as below:

STAGE No.	STAGE TIME (Mins)	TOTAL TIME (mins)	DYNO. SPEED (rpm)	ENGINE LOAD* (%)	TARGET $T_{HT\ Coolant}$ (°C)	TARGET $T_{LT\ CoolerOut}$ (°C)	ESTIMATED T_{Oil} (°C)
1	**2**	**2**	**Min. Idle**	**0**	80	45	TBA
ramp	0.5	2.5	Load.Idle	100	85	45	TBA
2	**2.5**	**5**	**Load.Idle**	**100**	85	45	TBA

ramp	0.5	5.5	1560	100	90	45	TBA
3	**9.5**	**15**	**1560**	**20**	90	45	TBA
ramp	0.5	15.5	2600	100	95	45	TBA
4	**13**	**28.5**	**2600**	**100**	95	45	TBA
ramp	0.5	29	2860	0	95	50	TBA
5	**2**	**31**	**2860**	**0**	95	50	TBA
ramp	0.5	31.5	2600	0	95	50	TBA
6	**2.5**	**34**	**2600**	**0**	95	50	TBA
ramp	0.5	34.5	2860	0	95	55	TBA
7	**2**	**36.5**	**2860**	**0**	95	55	TBA
ramp	0.5	37	2600	100	100	55	TBA
8	**13**	**50**	**2600**	**100**	100	55	TBA
ramp	0.5	50.5	1560	100	100	60	TBA
9	**10**	**60.5**	**1560**	**100**	100	60	TBA
10	**3 (ramp)**	**63.5**	**to 1800**	**100**	100	60	TBA
11	**3 (ramp)**	**66.5**	**to 1560**	**100**	100	60	TBA
12	**3 (ramp)**	**69.5**	**to 1800**	**100**	100	60	TBA
13	**3 (ramp)**	**72.5**	**to 1560**	**100**	100	60	TBA
14	**3 (ramp)**	**75.5**	**to 1800**	**100**	100	60	TBA
15	**3 (ramp)**	**78.5**	**to 1560**	**100**	100	60	TBA
16	**10**	**88.5**	**1560**	**100**	105	65	TBA
ramp	0.5	89	2600	100	115	70	110
17	**8**	**97**	**2600**	**100**	115	70	110
ramp	0.5	97.5	2860	0	115	70	110
18	**2**	**99.5**	**2860**	**0**	115	70	110
ramp	0.5	100	2600	0	120	70	110
19	**2.5**	**102.5**	**2600**	**0**	120	70	110
ramp	0.5	103	2860	0	120	75	110
20	**1.5**	**104.5**	**2860**	**0**	120	75	110
ramp	0.5	105	2600	100	120	75	110
21	**4**	**109**	**2600**	**100**	120	75	110
ramp	0.5	109.5	1560	100	125	75	110
22	**2**	**111.5**	**1560**	**100**	125	75	110
23	**2 (ramp)**	**113.5**	**to 1800**	**100**	120	70	110
24	**2 (ramp)**	**115.5**	**to 1560**	**100**	120	70	110
ramp	0.5	116	Load.Idle	100	115	60	TBA
25	**2.5**	**118.5**	**Load.Idle**	**100**	115	60	TBA
ramp	0.5	119	Min. Idle	0	100	50	TBA
26	**1**	**120**	**Min. Idle**	**0**	100	50	TBA

The 2hr test cycle dyno. speed / load and target coolant temperature profiles are shown below :





8.4 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 5 above, should be recorded at fixed points through the engine test cycle, (hereafter referred to as 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 1 in section 9.1 below).

The key point log parameters should be averaged over a 30-second steady-state running period and automatically initiated by the test bed control and automation system (for repeatability).

The recommended cycle timings for initiation of the 30s averaging periods for the key points logs, are shown in Table 1 below, aligned with 1 minute before the end of each test stage.

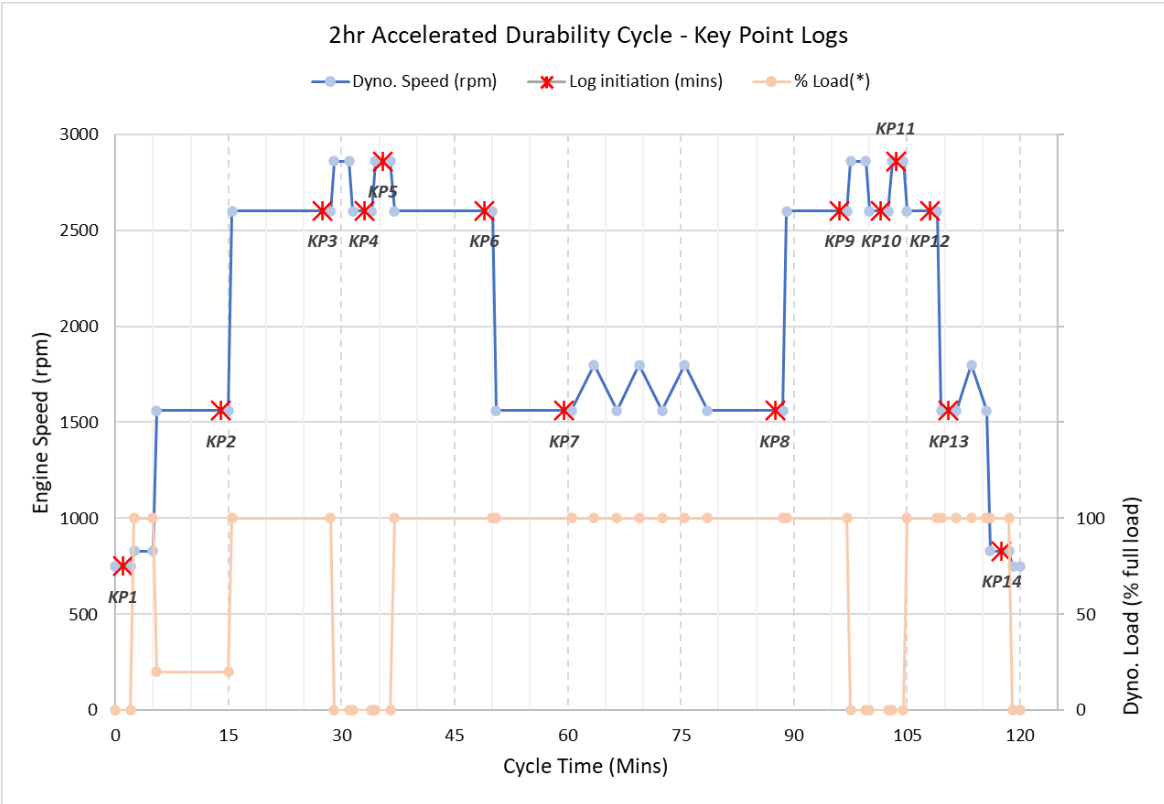
Additionally, it is recommended that the complete test duration is logged continuously at 1Hz so that in case of an engine durability, functional or performance issue, regular cycle data from preceding cycles may be examined and analysed to determine the possible onset of the issue, and assist in the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

TABLE 1 - 30S AVERAGED KEY POINT LOGS

KEY POINT No.	KP1	KP2	KP3	KP4	KP5	KP6	KP7
STAGE NO.	1	3	4	6	7	8	9
LOG START CYCLE TIME (Mins)	1	14	27.5	33	35.5	49	59.5
ENGINE SPEED (rpm)	Min. Idle	1560	2600	2600	2860	2600	95
DYNO.LOAD (%)	0	20	100	0	0	100	100

KEY POINT	KP8	KP9	KP10	KP11	KP12	KP13	KP14
STAGE NO.	16	17	19	20	21	22	25
LOG START CYCLE TIME (Mins)	87.5	96	101.5	103.5	108	110.5	117.5
ENGINE SPEED (rpm)	1560	2600	2600	2860	2600	1560	1560
DYNO.LOAD (%)	100	100	0	0	100	100	100

Graphical representation of the distribution of Key point logs throughout the 2hr test cycle :



8.5 TARGET TEST STAGE FLUID TEMPERATURES

This test includes variation of the engine coolant (HT & LT) fluid temperatures over the cycle, to defined target temperatures for each test stage (see 8.3 above for the targets).

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.

For the purposes of regulating the engine test temperatures against these requirements, 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)
    - Temperatures regulated 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 jacked-open version for this test)

- 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).
- 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
HT Coolant	Engine coolant outlet	± 5	125 (TBC)
LT Coolant	LT Radiator outlet	± 5	TBA
Oil	Oil gallery	± 5	110
Charge Air*	Intake manifold plenum (x2)	± 5	TBA

*Note: *"Limited natural power reduction is permitted at higher temperatures of charge air"*

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 slow speed ramping stages (10-15 and 23-24) 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. every 2 cycles or if below min. level. 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.

8.6 ENGINE WARM-UP

Following any engine stop the engine the engine temperature must be checked to determine if any warm-up operation is required before resuming the test sequence, as follows:

When Coolant Temperature is	Warm-up load operation (at 1560 rpm)
<45 deg. C	Run 25% load warm-up until >45 deg. C
>45 and <80	Run 50% load warm-up until >80 deg. C
>80	Run 65% load warm-up until aborted stage test conditions are achieved and then restart the stage >110 deg. C

The test bed cooling system target control temperature may be set to 115 deg. C to assist warm-up.

Unless otherwise specified, warm-up conditioning should be run at 1560 rpm (with load as specified above).

Note: All engine warm-up operation is considered 'off-cycle' and the running time should not be included in test time but logged separately as 'total engine hours'

8.7 SCHEDULED ENGINE STOPS

Following completion of at most every 4 cycles, the engine is to be stopped for a minimum of 5 mins. This stop time may be extended if required to perform any necessary scheduled or unscheduled in-cell inspection, servicing, or maintenance activities.

Longer stop periods and engine cooldown are expected to occur at least every 100hrs 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.

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. Any additional 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).

8.8 UNSCHEDULED STOPS

If an unscheduled engine stop is required (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 engine external & internal 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, following a suitable period of warm-up (as described in 8.6 above). 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.

As stated previously, any 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).

9 MONITORING, SERVICING AND REPORTING REQUIREMENTS

9.1 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 1 examples below) :

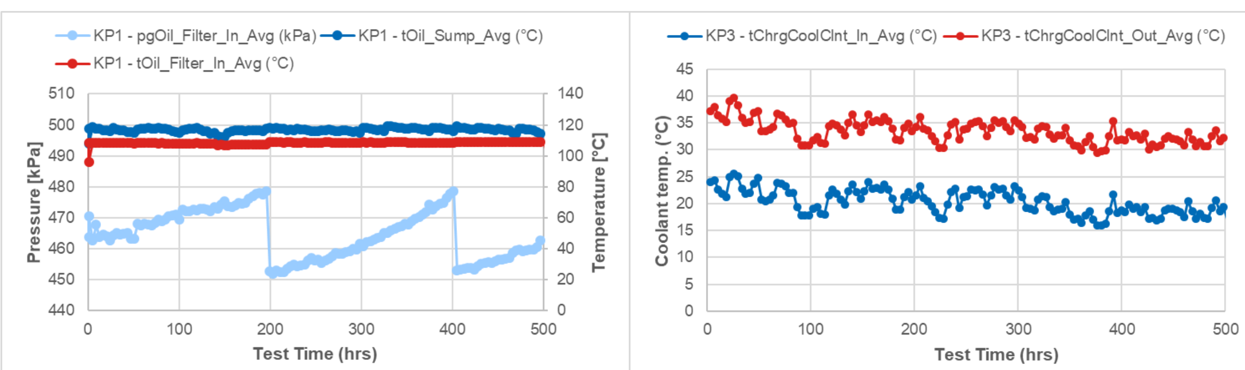


FIGURE 1 - EXAMPLE OF TEST TREND PLOTS

For this test the oil and oil filter should be replaced every 100hrs unless otherwise specified by the test engineer.

It is also important that oil quality is monitored throughout this test by rapid analysis of regular, more frequent, oil samples taken throughout the test. This will enable any need for more 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.

Similarly, any regular ongoing cooling fluid consumption must be investigated, noted, and monitored.

The results of regular engine leak detection inspections should be noted and monitored.

At 100hr intervals the results of the scheduled engine performance test should be cross plotted with previous results and reported.

An initial draft of the specific monitoring and servicing tasks required for this test are shown in Appendix 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 added, as the definitive design and associated FMEA activities progress, or based on observations made from any preceding GEN1 functional and durability testing.

9.2 Reporting

The BE1500 project engineering team should be advised by a daily email of the number of 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 1 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 performance checks), 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

10 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) o Crankcase blow-by is to be logged during this check • IR Thermal image recordings of the engine or individual components may also be requested
Oil Requirements	• Retain 100ml oil sample from the tank, ensure that it is clearly labelled • Drain oil and confirm volume removed from engine using drain and weigh method o 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	• Log any fluid or gas leakages o Photograph and record in logbook • 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.

11 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
- Intake manifolds
- 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.

12 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 400hr test duration.

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
- 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

APPENDICIES

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

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
	Pist[illegible] proud[illegible]	X	
Piston Pins	[illegible]ter of pin [illegible] 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 [illegible] roughness	X	
	[illegible]al cle[illegible] and [illegible]ing	X	
Rods	Big end diameters	X	X
	Big end diameters with bearings fitted	X	X
	[illegible]d surface roughne[illegible]	X	
	[illegible]	X	X
	[illegible] 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 Bore (with head plate fitted if required) [Bore distortion]	Cylindricity 1	X	X
	Cylindricity 2	X	X
	Cylindricity 3	X	X
	Cylindricity 4	X	X
	Cylindricity 5	X	X
	Cylindricity 6	X	X
	Cylindricity 7	X	X
	Cylindricity 8	X	X
	Cylinder 1 – 2nd, 3rd, 4th order	X	X
	Cylinder 2 – 2nd, 3rd, 4th order	X	X
	Cylinder 3 – 2nd, 3rd, 4th order	X	X
	Cylinder 4 – 2nd, 3rd, 4th order	X	X
	Cylinder 5 – 2nd, 3rd, 4th order	X	X
	Cylinder 6 – 2nd, 3rd, 4th order	X	X

	Cylinder 7 – 2nd, 3rd, 4th order	X	X
	Cylinder 8 – 2nd, 3rd, 4th order	X	X
Cylinder Head	Gas face flatness	X	X
	Gas face roughness	X	
	Valve guide diameter	X	X
	Valve stand [illegible]	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 diameter	[illegible]	X
	Cam thrust width	X	
	Cam roughness	[illegible]	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

Example Only
Build measurement list
to be defined during
definitive design phase

Note all fastener crack-off and back-to-mark torques to be noted on critical fasteners only.

APPENDIX 2 – RECOMMENDED TEST MONITORING REGIME

Action	Every 4 Cycles (8hrs)	Every 8 cycles (16hrs)	Every 12 cycles (24hrs)	Every 50 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
Perform engine leak-down and compression checks				Yes
Perform other monitoring measurements e.g. valve clearances, Crank TV measurement etc.(TBA)				Yes
Carry out engine performance test				Yes
Oil and filter change				Yes
Review all data before proceeding with test				Yes

* - More frequently if necessary

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