400HR DRIVING CYCLE

Test No.	BE-DUR-001	Engine Variant	GEN1	Issue level & Date	Issue 01 16 June 2021

1 TEST AIM

The DRIVING Cycle test aims to investigate the durability of the complete engine assembly and its various systems and components by performing a repeated cyclic 5hr test sequence. The cycle operates the engine between idle, peak torque speed and rated power speeds, at part and full engine loads, over a total duration of 400hrs.

This cycle is based on the endurance test requirements as described in Annexure 1 of the BE1500 project tender document and includes aspects of operation at 'normal' and elevated fluid temperatures.

The test also includes a small number of normal (ignition-off) stop-starts, as well as imitated vehicle engine stall-out events, enabled by intentional dyno overloading. Additionally, there is a small amount of operation up to the engine continuous overspeed condition.

2 GENERAL DETAILS

This test consists of a 21-stage 5hr cycle, repeated 80 times and comprises of :

- 20% of the test duration at Full engine load (10% each at rated power speed and peak torque speed)
- 30% at rated speed and 1% at continuous overspeed (80 occurrences)
- 15 % at minimum idling speed
- 60% of the test duration is with elevated (but within operating spec.) fluid temperatures representing hot ambient operation
- 80 scheduled normal engine starts, stops and cool-downs to ambient temperature (48 from hot running condition)
- 54 engine stall-stops from 1250 rpm & Idle initiated by dyno overload

(See section 8 below for full breakdown of cycle content and stage sequence)

Also,

- Oil & filter servicing every 200hrs (with interim oil sampling and ongoing analysis)
- Engine performance check every 100hrs

The objectives of this test are:

- Determine the robustness of engine systems and components over a simulated engine life cycle test
    - 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 and aid in the validation of oil and oil filter service intervals
- Assess system and component service life
- Determine any systems or areas of concern that would be at risk when the engine is used in service (in non-extreme environments)

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 and ensure 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 and vacuum 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 (and thoroughly cleaned) 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 @ 200hrs
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 also 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 testing 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 count of controlled stall events
- Ongoing incremental count of controlled hot coolant stops
- 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.

6 TEST SAFETY SHUTDOWN LIMITS

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

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 this test commencing, the following activities should be verified and completed (examine engine build book as some activities may have already been completed):

Measurements *(record in build / log book)*	• 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 ○ 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 • 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 • 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 ○ 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

The test sequence described in 8.3 below has been formulated to test the durability of the complete engine assembly and constituent systems over a 400hr test duration, running a multi-stage cycle at defined engine speeds and loads.

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 (the ramping stage time is counted as running time at the following test stage condition).

Test specification:

Parameter	**Unit**	**Value**
Time / Test Cycle	mins	300
Number of test stages / cycle	-	21
Ramp time between stages	s	20-30
Number of Test Cycles	-	80
Total Test Time	hrs	400

The cycle includes regular scheduled engine stop and cool-down events, alternating hot ambient and normal ambient temperature cycling, and simulated vehicle overload stall-out events described later.

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.

The target temperature requirements are detail in 8.5 below.

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 speed/load conditions and the total duration of each for this test are as described in Annexure 1 DRIVING CYCLE' load profile of the BE1500 project tender document, and summarised below:

Condition	Engine Speed (rpm)	Engine Load (%)	Total duration /cycle (mins)	%age of total test duration
Minimum idling speed	830	0	45	**15%**
Peak torque speed	1560	65	57	**19%**
Peak torque speed	1560	80	30	**10%**
Peak torque speed	1560	100	30	**10%**
80% of rated speed	2080	50	30	**10%**
85% of rated speed	2210	20	15	**5%**
Rated speed	2600	80	60	**20%**
Rated speed	2600	100	30	**10%**
Continuous overspeed	2860	0	3	**1%**
		Total:	**300**	**100%**

It is a test requirement that the engine is stopped for a minimum of 2 hours after every 2 cycles (10hrs) and allowed to cool-down until the dry sump tank oil temperature is within cell ambient +5 deg. C. See 8.7 below for details.

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

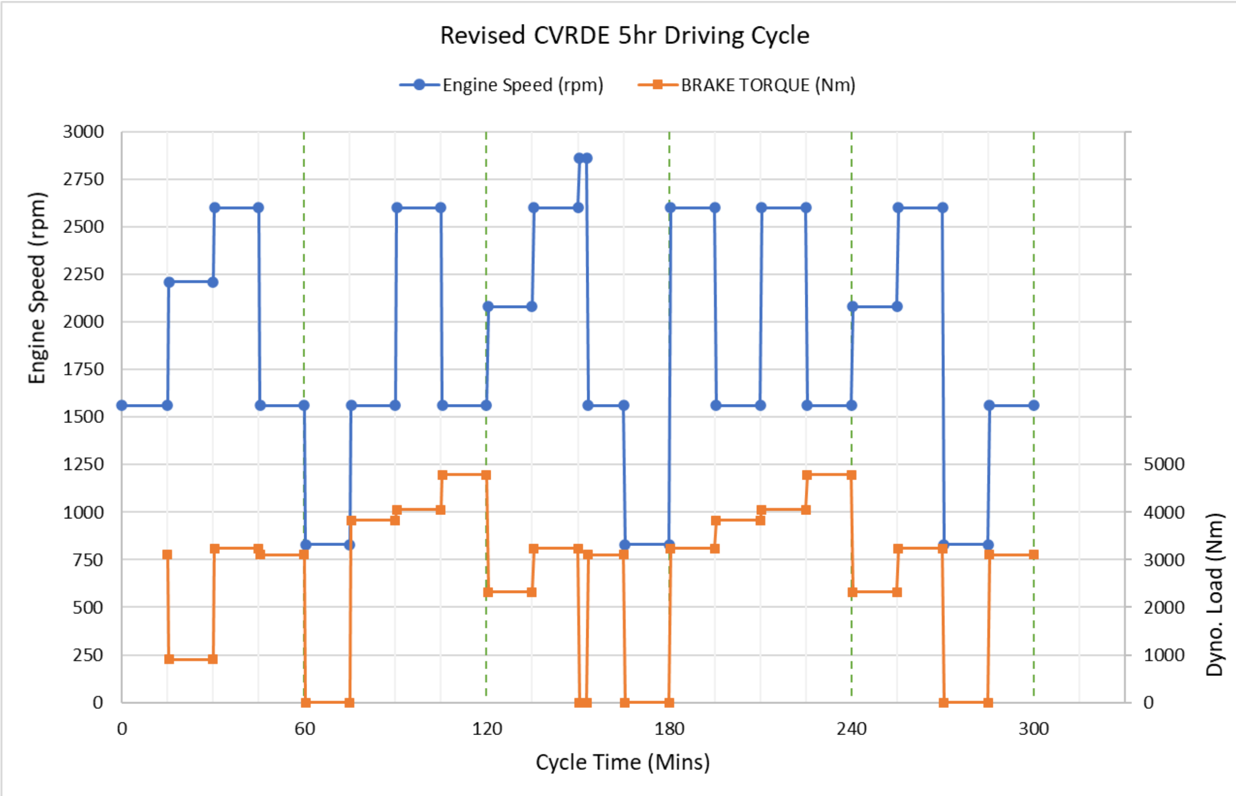
The test cycle is defined as below:

STAGE No.	STAGE TIME (mins)	TOTAL TIME (mins)	ENGINE SPEED (rpm)	ENGINE LOAD (%)	BRAKE TORQUE (Nm)	BRAKE POWER (kW)
1	**15**	15	1560	65	3109	508
ramp	**0.5**	15.5	2210	20	907	210
2	**14.5**	30	2210	20	907	210
ramp	**0.5**	30.5	2600	80	3242	883
3	**14.5**	45	2600	80	3242	883
ramp	**0.5**	45.5	1560	65	3109	508
4	**14.5**	60	1560	65	3109	508

ramp	**0.5**	60.5	Min. Idle	0	0	idle
5	**14.5**	75	Min. Idle	0	0	idle
ramp	**0.5**	75.5	1560	80	3826	625
6	**14.5**	90	1560	80	3826	625
ramp	**0.5**	90.5	2600	100	4053	1103
7	**14.5**	105	2600	100	4053	1103
ramp	**0.5**	105.5	1560	100	4783	781
8	**14.5**	120	1560	100	4783	781
ramp	**0.5**	120.5	2080	50	2324	511
9	**14.5**	135	2080	50	2324	511
ramp	**0.5**	135.5	2600	80	3242	883
10	**14.5**	150	2600	80	3242	883
ramp	**0.5**	150.5	2860	0	Min.	Min.
11	**2.5**	153	2860	0	Min.	Min.
ramp	**0.5**	153.5	1560	65	3109	508
12	**11.5**	165	1560	65	3109	508
ramp	**0.5**	165.5	Min. Idle	0	0	idle
13	**14.5**	180	Min. Idle	0	0	idle
ramp	**0.5**	180.5	2600	80	3242	883
14	**14.5**	195	2600	80	3242	883
ramp	**0.5**	195.5	1560	80	3826	625
15	**14.5**	210	1560	80	3826	625
ramp	**0.5**	210.5	2600	100	4053	1103
16	**14.5**	225	2600	100	4053	1103
ramp	**0.5**	225.5	1560	100	4783	781
17	**14.5**	240	1560	100	4783	781
ramp	**0.5**	240.5	2080	50	2324	511
18	**14.5**	255	2080	50	2324	511
ramp	**0.5**	255.5	2600	80	3242	883
19	**14.5**	270	2600	80	3242	883
ramp	**0.5**	270.5	Min. Idle	0	0	idle
20	**14.5**	285	Min. Idle	0	0	idle
ramp	**0.5**	285.5	1560	65	3109	508
21	**14.5**	300	1560	65	3109	508

Note: Target brake torque values here are specified based on post-CS Gateway extrapolated WAVE data (b309) and may be revised further during the definitive design phase.

The 5hr test cycle is shown in graphical form 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 (known 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 2 in section 0 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).

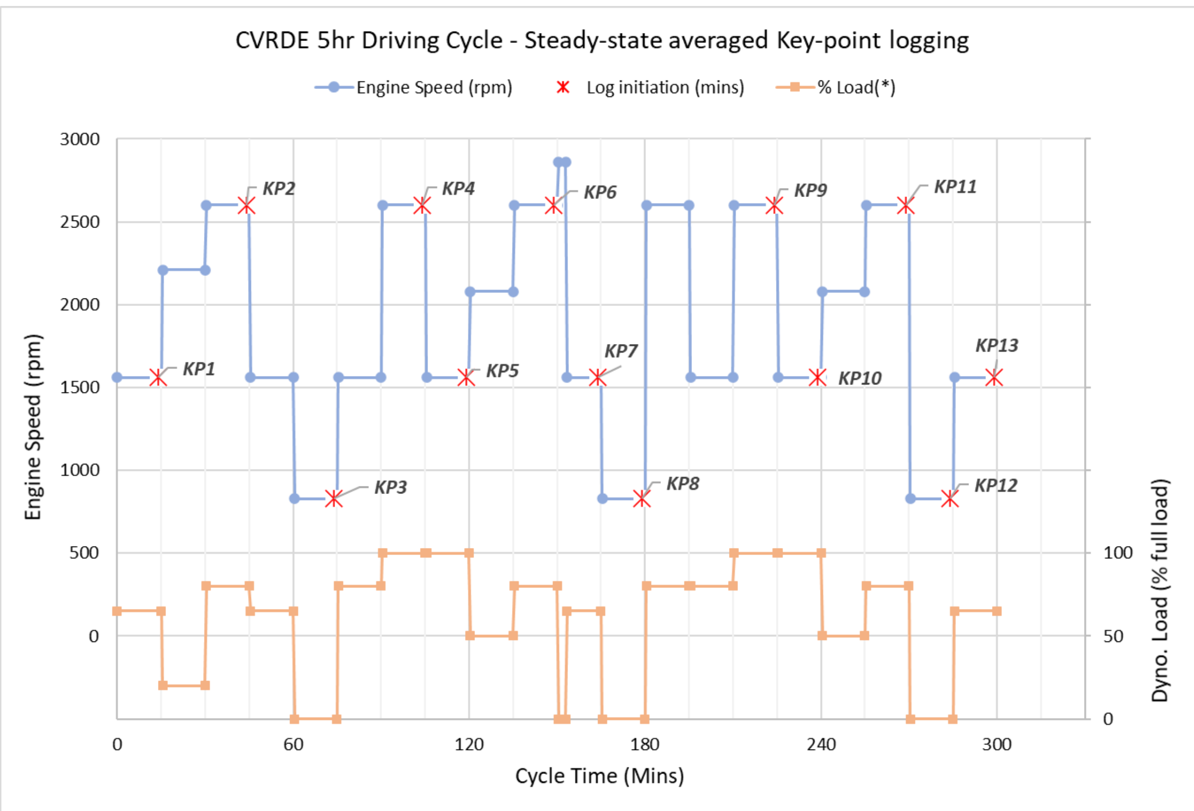
The recommended cycle timings for initiation of the 30s averaging periods for the key points logs, are shown in Table 1 below, aligned with 1 minute before the end of each test stage.

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	5	7	8	10	12
LOG START CYCLE TIME (Mins)	14	44	74	104	119	149	164
ENGINE SPEED (rpm)	1560	2600	Idle	2600	1560	2600	1560
DYNO.LOAD (%)	65	80	0	100	100	80	65
KEY POINT	**KP8**	**KP9**	**KP10**	**KP11**	**KP12**	**KP13**	
STAGE NO.	13	16	17	19	20	21	
LOG START CYCLE TIME (Mins)	179	224	239	269	284	299	
ENGINE SPEED (rpm)	Idle	2600	1560	2600	Idle	1560	
DYNO.LOAD (%)	0	100	100	80	0	65	

Graphical representation of the distribution of Key point logs throughout 5hr test cycle :



8.5 ALTERNATING HOT AND NORMAL TEMPERATURE CYCLES

The tender document states that the engine cycles should run at two controlled fluid temperature conditions summarised below :

	Number of cycles	Tender doc. Target Control Temperature range (deg. C)		
		Coolant	Oil	Charge Air
Set A (Hot running)	48	115-125	125-140 (TBA)	105-115 (TBA)
Set B (Normal running)	32	85-95	90-100 (TBA)	70-80 (TBA)

However, 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.

Current cooling system analysis is predicting the following temperatures for the two conditions **at rated power** :

Ambient condition (deg. C)	HT Coolant Engine in / out (deg. C)	LT Coolant radiator in / out (deg. C)	WCAC Air out (deg. C)	Oil Main gallery (deg. C)
Set A - 55	112 / 120	86 / 72	78	110
Set B - 25	82 / 90	55 / 42	48	TBA

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

Test bed control set points should be initially set as follows:

Parameter	**Unit**	**Cycle A - Hot**	**Cycle B - Normal**
HT Coolant Outlet Temperature	°C	120 +/- 5	90 +/- 5
LT Coolant Rad.Out Temperature	°C	72 +/- 5	42 +/- 5
Oil temperature	°C	No external control intervention planned, allow to float within engine limits	
Charge Air temperature	°C		
Fuel Temperature (LPFP in.)	°C	40 +/- 5	40 +/- 5
Air Intake Temperature	°C	30 +/- 5	25 +/- 5
Engine Speed	rpm	See Test Cycle Sequence	
Engine Load	%	See Test Cycle Sequence	
Rated Engine Speed	rpm	2600	2600
Rated Engine Power	kW	1103**	1103
Oil Level	Initial Max fill with Top-ups to Max. every 2 cycles or if below min. level. Monitor all additions and drain weights		

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

The cycles sets are to be run alternately in groups of 5 cycles (25hrs) i.e. A-B-A-B-A for 16 repetitions. However as there is also the requirement to stop the test after every 2 cycles, the repeating sequence becomes 8 repetitions of 50hrs as follows:

A-B- Stop -A-B- Stop -A-A- Stop -B-A- Stop -B-A- Stop (x8)

(Note this results in two back-to-back Set A cycles in the middle and the 48:32 ratio of set A:B cycles)

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

Upon first running this test cycle, the 1Hz logged actual cycle temperatures recorded over at least two continuous and 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 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.

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	Cycle A (Hot)	Cycle B (Normal)
<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 >110 deg. C	Resume previous test stage condition & restart durability sequence when >85 deg. C
>110	Resume previous test stage condition & restart durability sequence when >115 deg. C	N/A (Normal range is 85-95 deg. C)

The test bed cooling system target control temperature should be set to upper limit to assist warm-up (i.e. 115 deg. C for Cycle A, & 85 deg. C for Cycle B)

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 STOP & COOL-DOWN REQUIREMENTS

Following completion of every two cycles (10hrs) the engine is to be stopped and allowed to cool for a minimum of 2 hours **and**, until the bulk oil temperature in the scavenge tank is within +5 deg. C of the ambient temperature.

The tender document also instructs that :

- Following 15 Set A cycles and 16 Set B cycles the engine is shut down from 80 deg. C coolant temperature (Normal shutdown)
- Following 9 Set A cycles the engine is shut down from 105 deg. C coolant temperature (Hot shutdown)
    - 4 of these shutdowns should be initiated by dyno overload and stall-out of the engine (see section 8.8 below)
- During 5 Set A cycles and 5 Set B cycles the engine should be shut down every hour by dyno overload and stalling (i.e. additional 4 x 10 cycles = 40 stall-stops) – (see section 8.8 below)

Depending on whether the engine is to perform a hot shutdown (from 105 deg. C. coolant) or a normal shutdown (from 80 deg. C) the engine should be idled for a short period of time following the final stage 21 in the test sequence, with appropriate test bed cooling system control parameters set to ensure the coolant temp is within the required range (+/-5 deg. C) when it is stopped. This idling period should be counted as engine running time but not 'Test time'.

These requirements are encapsulated within the recommended repeating 100hr test sequencing shown in Appendix 2. (Note that the very last shutdown at the end of the 400hrs should be from 105 deg. C not 80 deg. C)

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 DYNO OVERLOAD ENGINE STALL-OUT REQUIREMENTS

The tender document states that 4 of the Set A hot engine shutdowns should be initiated by dyno overload and stalling of the engine. Also, that during 5 Set A cycles and 5 Set B cycles the engine is stopped by stalling-out every hour.

The proposed timings of these events during the test are shown in Appendix 2 –Test Sequencing. **Note that the hourly stall-stop events are deferred until the last 60hrs of the 400hr test.**

Figure 1 below shows the timing of the stall-out events within the test cycle, and the speed and load conditions at which the dyno overload process should be initiated. Note that in some cases this requires a slight departure from the usual cycle stage conditions, to reduce the engine speed and load, as described in Table 2 below.

The method for performing a dyno load-induced stall-out should be as follows:

- As the engine reaches the end of the test stage (or ramp) from which the stall-out event is to be triggered (the dyno speed control should be reduced to idle, engine power demand should remain at the initiation setting (i.e. do not reduce engine fuelling)

- Simultaneously the dyno load should be increased up to 4500 Nm as fast as may be achieved until the engine stalls-out and stops. Ensure that the peak dyno torque does not exceed 4850 Nm.
- Cycle engine ignition on/off and reset dyno control to idle mode & restart engine, monitoring carefully for any unusual noises from the dyno/engine driveline before resuming the test sequence.

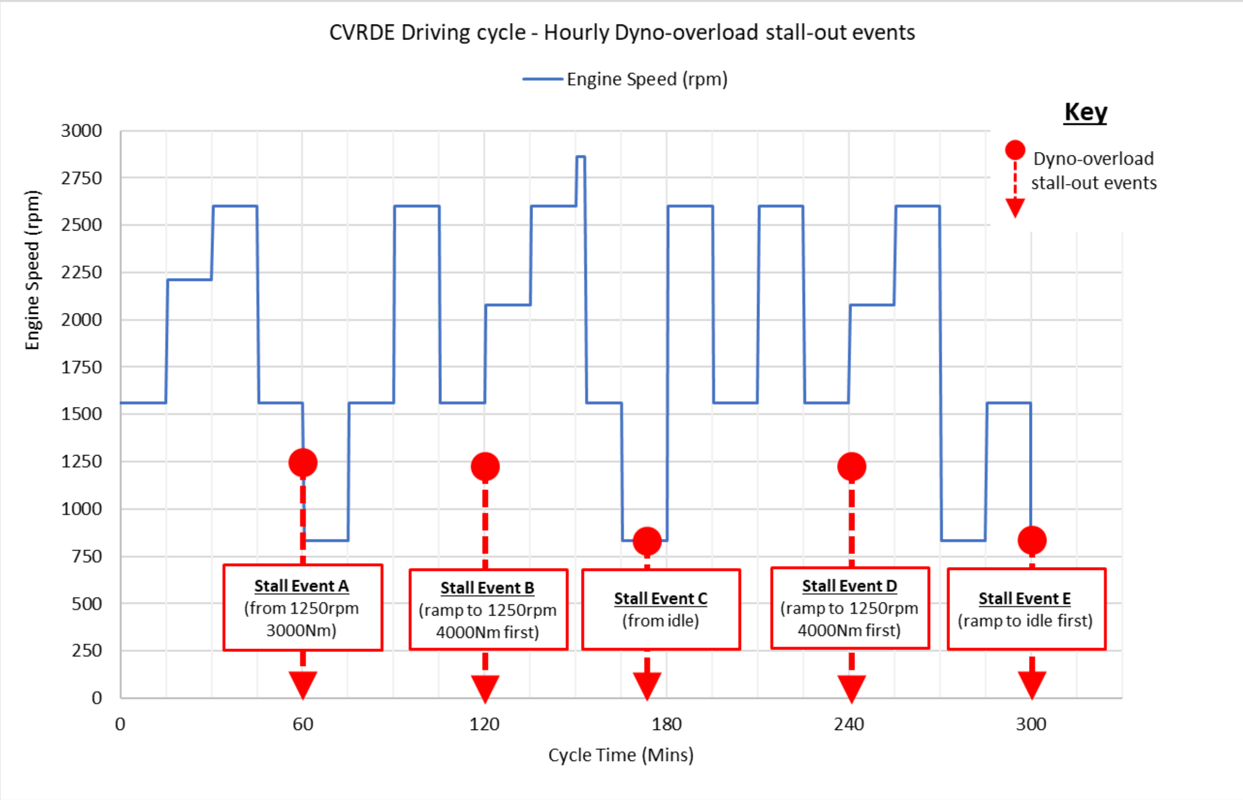


FIGURE 1 - PROPOSED DYNO-OVERLOAD ENGINE STALL EVENT TIMING AND CONDITIONS

Stall Event	TIMING & ACTION -	
	Prior to Initiation of dyno overload	**On engine restart**
A	Following completion of stage 4 (1560rpm / 65% load), ramp engine speed / load down to 1250rpm / 3000 Nm	Continue with stage 5 - Idle
B	Following completion of stage 8 (1560rpm / 100% load), ramp engine speed / load down to 1250rpm / 4000 Nm	Idle for 15s then ramp to stage 9 conditions – 2080rpm / 50% load
C	Midway through stage 13 (Idle)	Resume remaining Idle stage
D	Following completion of stage 17 (1560rpm / 100% load), ramp engine speed / load down to 1250rpm / 4000 Nm	Idle for 15s then ramp to stage 18 conditions – 2080rpm / 50% load
E	Following completion of final stage 21 (1560rpm / 65% load), ramp engine speed down to Idle	Resume warm-up or stage 1, as normal

TABLE 2 - CRITERIA AND METHOD FOR HOURLY STALL EVENTS

During the subsequent scheduled engine cool-down stop (i.e. every 10hrs) ensure that the driveline is inspected for any damage or deterioration (note this may entail removal of driveline safety guarding). The engine should also be manually barred over to check for any potential issues.

As described above engine restarting should alternate between electric and air starting.

8.9 UNSCHEDULED STOPS

The tender document states that:

" If the engine needs to be stopped during any cycle for any reason, the running time of that cycle shall not be counted as part of the test and the cycle shall be recommenced."

However, in the worst cases, if failure occurs near the end of the cycle, this could mean that almost 5 hours of test time would be disallowed and need to be repeated.

Therefore instead, it is recommended that only the test stage in which the unscheduled stop occurred, should 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.

For this test the oil and oil filter should be replaced every 200hrs 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. This will enable any need for more frequent oil servicing to be identified, or provide insight into ongoing engine wear, damage, or oil-ageing related issues.

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 2 examples below) :

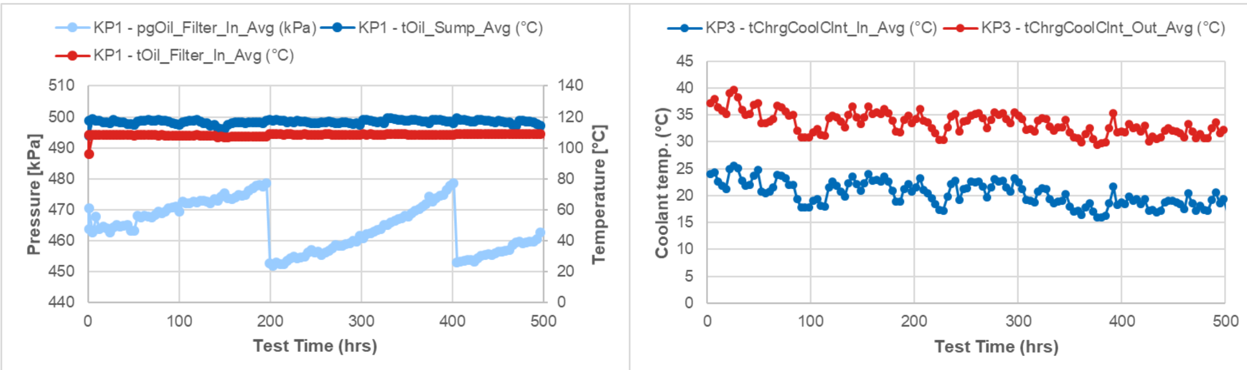


FIGURE 2 - EXAMPLE OF TEST TREND PLOTS

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 responsible 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 2 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) ○ 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 • Test engineer to confirm if drained oil can be discarded
Other Measurements *(record in build / logbook)*	• Post-test crankshaft TV performance (optional) • Cylinder leak down and compression on all cylinders - see procedure **BE-GEN-003** • Valve clearances (optional, if requested)
Checks	• Log any fluid or gas leakages ○ Photograph and record in logbook • Ensure Engine logbook is complete and up to date • Any parts removed from engine during test must be clearly labelled with engine no., 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 1200hr 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

13 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
	Piston stand[illegible]	X	
Piston Pins	[illegible] pi[illegible] in thr[illegible] p[illegible]sit[illegible]	X	X
	R[illegible]	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 widt[illegible]	X	
	C[illegible] surfa[illegible]	[illegible]	
	A[illegible] ce of [illegible] big end [illegible]	X	
Rods	Big end diameters	X	X
	Big end diameters with bearings fitted	X	X
	Big end surface roughness	X	
	Small en[illegible]ameters	X	X
	S[illegible] wi[illegible]h	X	X
	B[illegible] ar[illegible] is[illegible]	[illegible]	
	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

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

	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 diameters	X	X
	Valve stand pro[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	[illegible]	X
	Stem roughness	X	X
	Stem to seat run out	X	X
	Valve height	X	X
	Seat profile	X	X
Camshaft	Journal diameters	[illegible]	X
	Cam thrust width	[illegible]	
	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 all fastener crack-off and back-to-mark torques to be noted on critical fasteners only.

APPENDIX 2 –TEST SEQUENCING AND MONITORING REGIME (EVERY 100HRS)

Cycle Time (hrs)	Test condition(s)	Power check	Oil sample	Oil / filter change	Overload & Stall out	Hourly stall-out *
5	Cycle A					
10	Cycle B					
10	80°C coolant Stop & cool					
15	Cycle A					
20	Cycle B					
20	80°C coolant Stop & cool					
25	Cycle A					
30	Cycle A					
30	80°C coolant Stop & cool		Yes			
35	Cycle B					
40	Cycle A					
40	105°C Hot coolant Stalled Stop & cool				Yes	
45	Cycle B (Stall stop every hour)*					(>345)
50	Cycle A (Stall stop every hour)*					(>345)
50	80°C coolant Stop & cool		Yes			
55	Cycle A (Stall stop every hour)*					(>345)
60	Cycle B (Stall stop every hour)*					(>345)
60	80°C coolant Stop & cool					
65	Cycle A (Stall stop every hour)*					(>345)
70	Cycle B (Stall stop every hour)*					(>345)
70	80°C coolant Stop & cool					
75	Cycle A					
80	Cycle A (Stall stop every hour)*					(>345)
80	105°C Hot coolant Stop & cool		Yes			
85	Cycle B (Stall stop every hour)*					(>345)
90	Cycle A (Stall stop every hour)*					(>345)
90	80°C coolant Stop & cool					
95	Cycle B (Stall stop every hour)*					(>345)
100	Cycle A					
100	**80°C coolant Stop & cool****	Yes	Yes	@200hrs		

* - Hourly stall stops are only required in final 55 test hours (i.e. 345+ hrs)

**** - Final test stop at 400hrs to be 105°C Hot coolant**