DIGIta MANufacturing and Proof-of-Process for Automotive Fuel Cells

DIGITAL MANUFACTURING AND PROOF-OF-PROCESS FOR AUTOMOTIVE FUEL CELLS

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DELIVERABLE 2.2: STACK COMMISSIONING HANDOVER BASELINE REQUIREMENTS

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PU	*Public*	***Y***
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NATURE OF THE DELIVERABLE		
R	*Report*	***Y***
P	*Prototype*	
D	*Demonstrator*	
O	*Other*	

SUMMARY	
Keywords	*DIGITAL MANUFACTURING AND PROOF-OF-PROCESS FOR AUTOMOTIVE FUEL CELLS – STACK COMMISSIONING HANDOVER (BEGINNING OF LIFE – BOL) REQUIREMENTS*
Abstract	*This deliverable report presents a summary of the Beginning of Life (BoL) handover requirements for Intelligent Energy's automotive fuel cell stacks. As targets for quality and throughput need to align with contemporary, at rate, single-piece-flow automotive production; scenarios for direct ship-to-line drop-in / drive-off handover need to be modelled and pre-conditioned functionality benchmarks specified. "Best in class" practises (e.g. The Toyota Production System) are applied by Toyota. Performance, life expectancy, environmental compatibility and robustness of life targets will factor within an ensuing BoL test procedure (Task 2.3). This, together with an exemplar for stack assembly, as derived from WP4 outcomes for the Blue-print design, will enable the modelling of the stack process flow and development of digital cause and effects (T6.3) capability via Discrete Events Simulation (D6.3), thus, underpinning MRL6 attainment. Models for operational expense (OPEX) based Inputs into Task 2.4 (Technical Cost Modelling – Stack Assembly) will be enabled.*
Public abstract for the public website (only for confidential deliverables)	

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DELIVERABLE 2.2 STACK COMMISSIONING HANDOVER BASELINE REQUIREMENTS

CONTENTS

NOMENCLATURE

Symbol or acronym	Description
AC	Air Cooled
IE	Intelligent Energy
KPI	Key Performance Indicators
BoL	Beginning of Life
EoL	End of Life
PoP	Proof-of-Process
QC	Quality Control
VoC	Voice of Customer
ICE	Internal Combustion Engine
TMUK	Toyota Motor Manufacturing, UK
OEM	Original Equipment Manufacturer

1. Introduction

1.1. General

DIGIMAN WP2: Requirement Setting & PoP Measurement involves the setting of requirements to i) capture VOC (Voice-of-the Customer) in demonstration of the to-be-developed Blue-print design's deployment readiness as demonstrated by operation and measurement of the Proof-of-Process uplifted automation, and ii) to demonstrate attainment of the project's pre-determined and below-stated key objectives:

- Demonstrate that, via the uplifted automation, the blueprint design as configured as fully integrated assembly and test line, would scale to deliver production capacity >50,000 stacks/year by 2020
- Demonstrate for a single line a total stack power output of >5MW
- Demonstrate a step improvement of cell assembly cycle times from today's semi-automated >22 seconds per cell to automated processing at <5 seconds per cell (x5 times uplift)
- Advance stack manufacturing technology level to MRL6
- Develop in-process quality controls at component and sub-component level to reduce scrap rate to target <3%
- Model costs showing target trajectories consistent with automotive targets for 2020 at 50k stacks pa
- Ensure that the stack performance is not detrimentally affected by the improvements for manufacturing and assembly delivering 0.7 A/cm2 @ 0.7V world leading for air cooled fuel cell technology

The specific scope objective from FCH-01.1-2016 work plan is to 'Transpose established automotive industry best practices on production and quality to the manufacturing of PEMFC stack and stack components.

1.2. Stack Commissioning Handover Baseline Requirements

WP2 Task 2.1 Deliverable 2.1 provided definitions for automotive best-practice, and specification of baseline KPIs for fully automated stack assembly and test. The DIGIMAN Project's ensuing automation uplift, as demonstrable and measurable (at a down-scaled rate) via the PoP Demonstrator, will be used within a modelled process flow as the exemplar to support the development of digital cause and effects (T6.3) capability via Discrete Events Simulation (D6.3).

WP2 Task 2.2 Deliverable 2.2 details Toyota "best in class" Automotive Vehicle & Engine QC requirements. It allows equitable benchmarking to Internal Combustion Engine (ICE) production's quality standards and throughput targets, against which, automotive Fuel Cell stack assembly & test must aspire. In satisfying the modelled output targets, via a single piece flow pull system, with an auto maker's, at rate, vehicle assembly line, a lean transition for direct ship- to-line and drop-in / drive-off scenarios becomes a viable proposition, thus, underpinning MRL6 attainment. Cost data for the modelling of operational expense (OPEX) based Inputs into Task 2.4 (Technical Cost Modelling – Stack Assembly) will ensue.

Deliverable 2.1 defines the Fuel Cell Stack performance (Sections 3.1) and manufacturing metrics (Section 4.1) against which output from the Stack commissioning handover will be measured.

2. Vehicle Quality Control

2.1. Toyota unique approach to vehicle quality – Superior quality built in

Toyota has achieved a reputation for the production of very high-quality vehicles in all countries around the world. This has been achieved by an approach to quality control and quality assurance, which is unique to Toyota and has been developed over many years. From the early stages of the design process up until the vehicles come off the line, quality is key.

To achieve total quality control, standardised work is used together with visual control to clearly indicate the current status and make it very easy to spot problems. Each member is responsible for the quality of their work and aims never to pass on poor quality to the next stage (build in quality). If anything unusual is noticed, the member can stop the process. Rigorous scrutiny of key features and functions of each vehicle helps to confirm both the quality of the vehicle and the stability of the production process to the vehicles at every process.

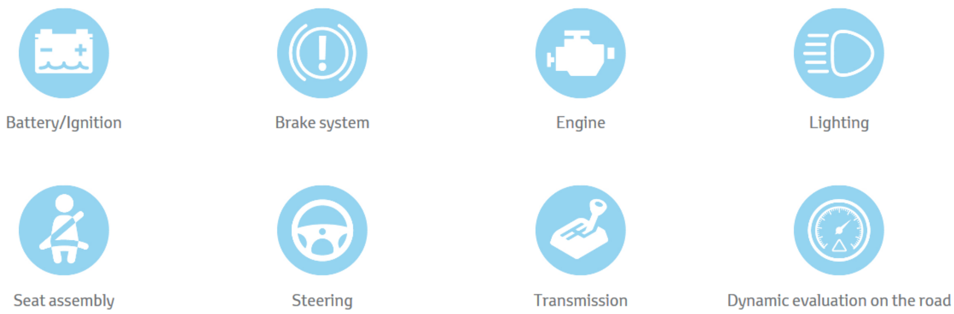
Quality assurance activities are carried out based on the three quality principles:

- Customer expectation determines the quality required.
- Quality is built in at every stage of the process.
- Quality is continuously improved (kaizen)

The people who build Toyota vehicles take a personal pride in the quality of their work. Every vehicle will undergo thousands of quality checks in the course of the manufacturing process.

The process of building a vehicle involves many people working in sequence on many different tasks. Everyone on the production line has a responsibility ensuring quality at every stage, a personal engagement in the job that culminates in the quality assurance checks that are carried out before any vehicle leaves the factory.

Main quality checks made in Toyota manufacturing plants



2.2. Toyota Europe Manufacturing Plants

Toyota in Europe has nine manufacturing centres building cars, engines and transmissions across the continent, each one committed to delivering ever better cars for our customers. With a workforce of more than 17,000 people dedicated to building not just the nine different models manufactured in Europe, but also most of the engines and transmissions used as well.

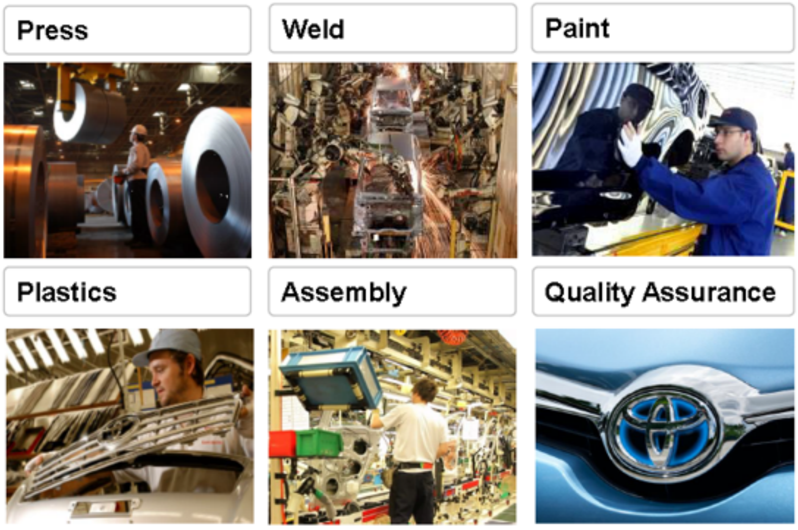
There are six vehicle plants, located in France (Yaris), the UK (Auris), Turkey (Verso, Toyota C-HR and Corolla), the Czech Republic (Aygo), Russia (Camry and RAV4) and Portugal (Land Cruiser for export). There are engine and transmission manufacturing facilities in Poland and the UK. Not only do these supply local markets, they also produce vehicles that are exported around the world (see as follows).

2.2.1. Vehicle manufacturing at Toyota Motor Manufacturing, UK (TMUK)

Since 1992 in TMUK production facility at Burnaston millions of vehicles have come off the production line. The factory has built 11 different cars, with more than a hundred versions to build.

Vehicle production is a complex process consisting in step-by-step creation of a new car. A total of 825 processes have turned sheet steel and parts into a fully functioning, road-legal car in a little more than 12 hours.

Main shop areas at TMUK Burnaston



At every stage in the vehicle's construction, product checks and inspections are regularly carried out by both machines and humans. Faults are addressed and rectified immediately so that imperfections are not passed on further down the line. This element of the Toyota Production System is known as Jidoka.

In each shop both people and machines are backed by a diligent quality assurance team, whose job it is to regularly inspect the machines and components. Within the Toyota Production System, this is known as Genchi Genbutsu.

Quality Assurance

The Quality Assurance department consists of a team of skilled workers who will put the car under the microscope one final time. They will carry out over 2,000 checks on every car before it leaves the factory. It's all part of Poka-Yoke – one of the values of the Toyota Production System that translates as 'mistake-proofing'.

A list of quality assurance series of tests includes:

- Cars arrive from the Assembly Shop on an overhead gantry. Their first stop in Quality Assurance is the interior check team, where it takes 15 minutes to examine every part of the interior.
- Next to be inspected for quality of fit and finish is the bodywork and exterior trim. This is where the most sensitive tools in the factory are used for the first time – members' hands. They're trained to feel along the body panels and panel gaps to check for imperfections or inconsistencies. However, finding any faults would be a surprise. Each car has passed numerous inspections already, and built-in quality processes mean that faults are spotted and fixed long before the car reaches this point.
- Once the interior and exterior checks are complete, the engine is started. In fact, as a car makes its way through Quality Assurance the engine will be started and stopped six times.

- In the function line, the underbody is checked and the fit and finish of the exhaust and floor pan is scrutinised. Then while the steering alignment is fine-tuned, bolts and fixings are double-checked for security. The headlamp height, angle, beam and brightness are examined to ensure brightness and reach, and there are eight different types of brake light to check – each designed to comply with different legal requirements in the 56 countries to which the cars are shipped.
- Everything now aligned, each car heads to a rolling road for a series of running and brake tests. Here it is accelerated to speeds of up to 70mph and the functioning of the anti-lock braking system is checked. External systems like windscreen wipers are also put under the spotlight.
- Soon afterwards, the car is subjected to a special leak test that drenches it with more than 900 litres of water in a specially adapted shower room. It's the equivalent of driving through water pressure that exceeds the heaviest recorded monsoon. Naturally, all the water is recycled back into the system and reused.
- The last inspection is in the light tunnel to confirm once again that the paintwork is up to standard and that there are no scratches or dents.

Toyota's faith in the quality of the cars produced at Burnaston is reflected in their five-year, 100,000-mile warranty. There is no mileage limitation for the first year, and any mechanical fault caused by a manufacturing defect is covered.

It's a testament to the build quality in the Press Shop, Weld Shop and Paint Shop that every Toyota also comes with a 12-year anti-corrosion and anti-perforation warranty. This offers protection against rust affecting sheet metal body panels as a result of manufacturing faults, and is transferable to future owners. There's also a three-year unlimited mileage paintwork warranty covering defects and surface rust as a result of a manufacturing defect.

Hybrid models come with an additional five-year, 100,000-mile warranty covering all hybrid components and the hybrid battery.

2.2.2. Engine Manufacturing at Toyota Manufacturing UK (TMUK)

One of the Toyota Engine Plant is located at Deeside (UK) employing over 500 members on a site covering 115 acres.

Engines are produced through a process of Aluminium casting, Machining and Assembly before final inspection and dispatch to vehicle plants. There are 329 individual parts in a hybrid engine and it takes 137 people to build a single engine. Currently, an average number of 950 engines come off the production line per day, equivalent to one engine every 57 seconds.

178 in-depth quality checks on the machining and assembly of engines are carried out. To ensure maximum engine efficiency, components are machined to 3-micron tolerance. It takes 50 assembly-line processes to produce a hybrid engine.

As engine components move down the assembly line, certain parts will be randomly pulled off the line and measured for variations in size. In some cases, Toyota is checking for variations that are much smaller than the diameter of a human hair. This quality control procedure helps to ensure that critical engine parts are machined to very strict specifications. If the selected part is slightly smaller or larger than the one that came before it, the entire batch of parts is purged from the line and the machine that makes them is adjusted for accuracy.

It is necessary to test the functionality of an engine prior to installing in a vehicle. End-of-line test are to catch any defects missed during engine assembly

A hot test system is a production test used to check all the engine operating parameters as they would function real-time in an actual vehicle. A hot test is performed with a frequency of 1% (1 engine out of 100 manufactured engines).

A cold test consists of a leak test, which includes the testing of all cavities and systems that must not leak, such as oil, water, fuel and air. The second feature of a cold test procedure is dynamic cold testing; where all engine functions are tested while the engine is driven by an electric motor at various speeds. A cold test is applied to each engine.

One of Toyota's most rigorous engine tests takes randomly selected engines and revs them from idle to 6000 rpm 200,000 times. A car would have to make 50,000 full-throttle runs up a freeway on-ramp or spend 10 years at the hands of a taxi driver to repeat such a torturous process. Although most drivers would never subject their own car to such stress, Toyota knows that a tough engine is a more reliable engine.

Toyota randomly selects completed engines and subjects them to 180 hours of full-throttle operation. This test is equivalent to driving a vehicle at maximum speed for 7.5 days-non-stop. The test checks the strength and durability of parts like the crankshaft, bearings, connecting rods, pistons, valves and camshafts. If the engine can survive 180 hours of high-rpm abuse, then years of commuting will seem like a walk in the park.

2.3. Fuel Cell Vehicle Manufacturing at Toyota Motor Corporation (Japan)

Toyota produces the first commercial fuel cell vehicle, the Mirai, in the Motomachi Plant in Toyota City since November 2014 with a production line that will deliver 3000 vehicles by 2017.

Established in 1959, Motomachi was Toyota's first plant devoted to passenger cars and has produced models such as the Publica, Corona, Cresta, Soarer, Supra, RAV4, and the Lexus LFA supercar.

The assembly line for the Toyota Mirai is divided into three main sections: trim, chassis/fuel cell assembly, and final assembly. In each section, there are sub-assembly areas for parts installation where Toyota applied the same in build quality philosophy for each part and process. Before assembly the fuel cell stack, each of the 377 constituting cell is checked for leak and performance.

Considering that most of the time for the specific inspection on each cell is mainly due to preparation of the cooling set-up, Toyota developed an indirect cooling system, validated against actual performance, to enable about 80% reduction of inspection time.

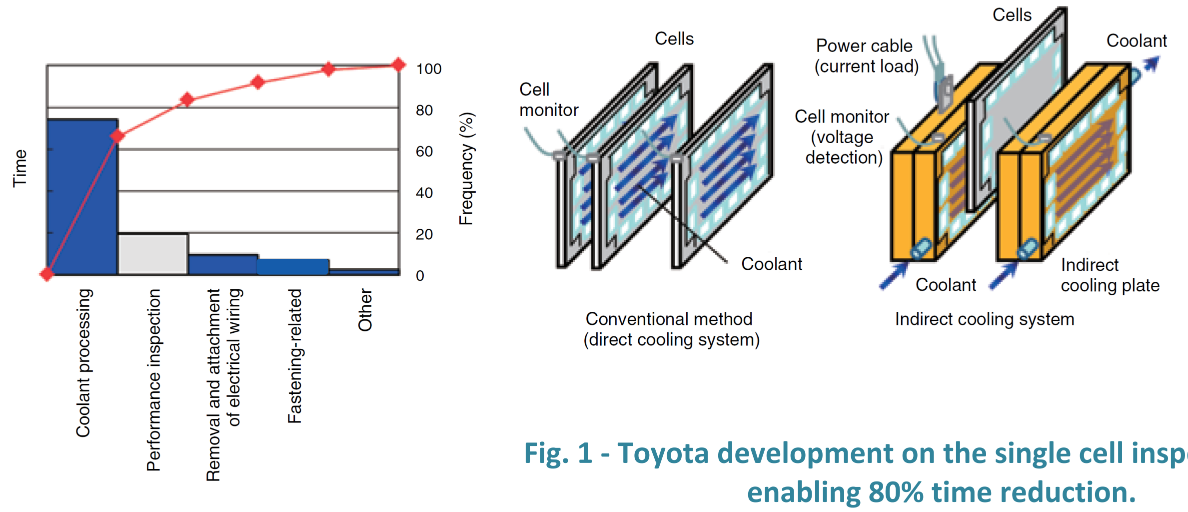


Fig. 1 - Toyota development on the single cell inspection set-up enabling 80% time reduction.

The Toyota Mirai features a Carbon Fiber Reinforced Plastic stack frame which is produced at the assembly area of Toyota's Motomachi Plant. Following the installation of the fuel cell stack, the boost converter, hydrogen tank and tubes are fitted to the vehicle.

A leak test is performed using helium. Next, the vehicle's fuel cell stack and hydrogen tanks are installed at the same time, followed by preparation of the electric motor and connection of the air compressor to the fuel cell stack. Before the chassis assembly is complete, the drive shaft, front axle, inverter, water heating unit, high voltage cable, front suspension, motor, rear axle, front bumper and wheels are installed.

Fig. 2 – installation of the fuel cell stack in the Mirai vehicle at Motomachi plant.

The final processes before the Toyota Mirai fuel cell sedan rolls off the assembly line are the installation and assembly of the external power supply system, vehicle interior, engine bay, windshield, and rear windows. An ignition check is then performed on the vehicle before it is sent for final inspection.

Fig. 3 – Final inspection of the Mirai at Motomachi plant.

Detailed quality control and inspection is performed on the Toyota Mirai before it leaves the Motomachi Plant, on its way to customers. Toyota specialists use both visual and tactile inspection to ensure the vehicle is of the highest quality and without any defect before leaving the factory.

2.4. General OEM ICE & Battery QC Testing Sequence

2.4.1. ICE In-line Testing

Automotive OEM's perform a number of in-line tests to ensure no defects before the engines are assembled in the vehicle.

In-line tests

- Torque to turn test: This test is done to identify any protrusions of the piston after assembly in the engine. This test helps in the selection of appropriate head gaskets.
- Torque to turn test: This test is also done to ensure positioning of the cam shaft in the engine.
- Cylinder head, block leak test: This test is done in the cylinder assembly line when all the valves and collets are assembled. This test is purely for the cylinder head. Individual leak tests are done at the machining stage for each component where leaks are possible.
- Oil and water cavity leak test (Pressure decay): Once all the engine parts are assembled, this test is done to identify any leaks in the cylinder block, head, cam shaft and pump.
- Leak test: The above mentioned test is then done to identify leaks in components that are susceptible to early wear such as piping, coolant cavity and hoses.
- Sniff test: This forms a part of the leak test where a gas is used to sniff any leaks during the leak tests.
- Cold test: This is the last of the in-line tests that is carried out without any fuel.

Functionalities such as noise, vibration, sensor feedback, continuity from harnesses, torque to turn of components are all checked for every engine that is manufactured. The duration of this test is about 1.5mins.

2.4.2. Off Line ICE Tests

- Hot test: This is similar to the cold test with the only difference being that the actual fuel is used to run the engine. This test is carried out for a batch when the engines initially come off the line and the frequency reduces depending on the results. The duration of this test can vary anything between 3min to 15 min depending on the engine variants and the results observed.

- Dyno test: This test is done on a dyno to replicate the assembly conditions in the car as much as possible. This is carried out once a week or once a month depending on results from the batch production. All the engines that are tested on the dyno are then stripped down to individual components and analysed.

2.4.3. Automotive OEM Battery Testing

In-line

- Cell impedance and polarity – Every cell is tested for polarity and impedance before insertion into module carrier.
- Weld verification- Check every weld for integrity using current-voltage profile. Temperature sensors, pyrometers, used for pulsed arc welding. In case of wire bonding (ultrasonic), a pull test is done to identify strength of bond.
- Cooling system test- A leak test is done to look at pressure decay in the module assembly.
- End of line test- pressure and leak tests, insulation test and voltage proof, various performance tests as well as testing and integration of the Battery Management System (BMS).

Pack level

- Harness test- Check for integrity of harnesses.
- Leak test- This test is done after assembly of the pack into housing.

3. Current IE AC Fuel Cell Stack Commissioning / Handover Process

The principal stages and elements of the current IE AC fuel cell stack commissioning / handover process are as follows:

3.1. Stack Assembly - 100% In-line Cell Test

In terms of stack assembly and test, the cells are considered as incoming components of the stack assembly, so cell testing can be considered as upstream incoming Quality Control testing. This consists of:

- Pressure decay (leak) test. The cell is compressed in a fixture to just above its final working dimension, then is filled with compressed air with the exit dead-ended. The pressure decay of this closed system is measured and compared against an acceptable upper limit.
- Through-flow test. The cell is compressed in a fixture to just above its final working dimension, then is filled with compressed air with the exit open to atmosphere. The resulting flow rate is measured and compared against an acceptance range.
- Weight test. Each complete cell is weighed and compared against an acceptance range to confirm it contains the correct number and type of components.

3.2. Post Stack Assembly Test

The assembled stack undergoes a number of post-build quality tests before being passed onto final commissioning handover and performance testing:

- Helium flow leak test. The stack is filled with Helium with the exit dead-ended, and the resultant leakage flow rate compared against an acceptable upper limit.
- Pressure decay (leak) test. The stack is filled with compressed air with the exit dead-ended. The pressure decay of this closed system is measured and compared against an acceptable upper limit.
- Through-flow test. The stack is filled with compressed air with the exit open to atmosphere. The resulting flow rate is measured and compared against an acceptance range.

3.3. Stack Commissioning / Handover Test

In order to test stack performance, a test rig with the following features is required:

- Hydrogen gas (fuel) supply.
- Safety equipment associated with use of hydrogen gas, such as flashback arrestors, leak and fire detectors and local exhaust ventilation hood.
- Programmable power supply and electronic load units.
- Thermocouple temperature monitoring.
- Data acquisition and logging system, automated control software.

The stack handover test incorporates three complementary processes:

- Health checks to check for cell and stack build quality and safety.
- Absolute performance test under standardised reference conditions against acceptance limits.
- Conditioning to moisten the fuel cell membranes and build up performance.

Each test process contains the following elements:

Health checks

- Pressure decay leak test.
- Cell Voltage Monitoring check to ensure data can be read from all individual cells.
- Voltage measurements under various conditions to identify different potential cell quality issues.

Performance testing

- Stack current at fixed stack voltage (or fixed mean cell voltage) versus a lower acceptance limit.
- Mean cell voltage at fixed stack current versus a lower acceptance limit.
- Stack power at fixed stack current versus a lower acceptance limit.
- Cell voltage balance. Individual cell voltages are measured at fixed stack current, and the measured range in cell voltages compared against an upper acceptance limit.

- Polarisation curve. Mean cell voltage is plotted against a range of stack load currents to map out performance across the total range of the operating envelope.

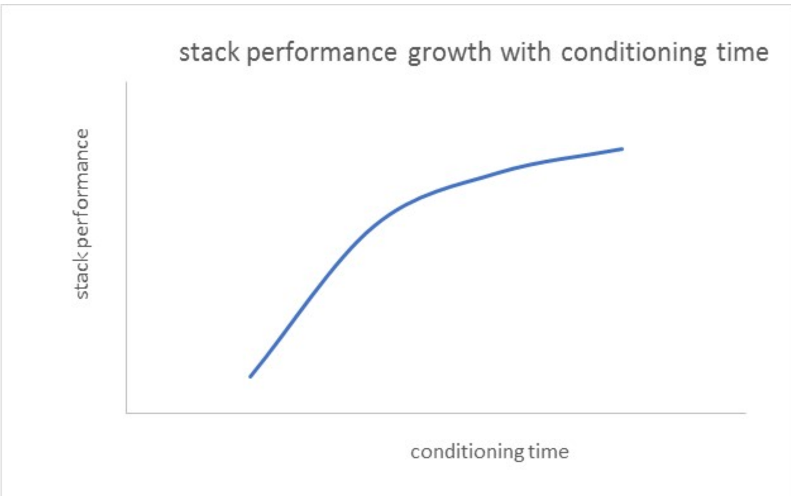
3.4. Post-test Leak Checks

After the stack is removed from the performance test rig, it undergoes repeat leak testing as follows:

- Helium flow leak test. The stack is filled with Helium with the exit dead-ended, and the resultant leakage flow rate compared against an acceptable upper limit.
- Pressure decay (leak) test. The stack is filled with compressed air with the exit dead-ended. The pressure decay of this closed system is measured and compared against an acceptable upper limit.
- Through-flow test. The stack is filled with compressed air with the exit open to atmosphere. The resulting flow rate is measured and compared against an acceptance range.

4. Conditioning Period

Fuel cell stack performance at Beginning of Life (BoL) is very dynamic; performance initially improves dramatically with time as the membrane generates and retains moisture. Consequently, reference performance tests must be made under the same conditions and after the same length of time in order to be robustly comparable against targets and other stacks. The duration of conditioning is a compromise between achieving acceptable BoL performance versus too long a test adversely affecting production test throughput. The chart below illustrates how the number of stack performance increases with conditioning time:



5. Recommendation & Future Work

Traditionally, IE has focussed conditioning test times to be most appropriate for Research and Development purposes as stack QC handover testing at modest production volumes has not been a bottleneck to date. Hence, a multi-hour conditioning / handover test has been used as the standard baseline test duration for consistent comparison purposes. A sequence of stack Design of Experiments has been undertaken, to establish factors which may correlate to accelerated handover test performance, leading to reduced duration stack conditioning / handover testing. This shortened test methodology has been trialled on a small sample of AC64 stacks.

Further work is required to ensure that these factors are robust, relate to the latest generation of IE AC64 stack technology and do not have a detrimental effect on the intended product application. This will be covered in WP2 Task 2.3 of the DIGIMAN Project and reported upon within the Deliverable Report D2.4 at month 24. IE will interpolate performance, life expectancy, environmental compatibility and robustness of life targets for the AC64 stack and derived a BoL test procedure, leak rates, conditioning phase linked with the acceptance criteria fixed by automotive expectations. Different conditioning phases will be evaluated in order to optimise the duration of the test and as a consequence the cost of this stack acceptance activity both in terms of infrastructure and operation. IE is targeting a total 30 minute functional and performance QC test as a replacement for the current multi-hour duration test.

Automation of stack connectivity to the test rig and incorporated conditioning / handover test communications within a single-piece flow line offers possible alignment and harmonisation with typical auto makers', at rate, single piece flow. This will be modelled, as direct-to-line drop-in / drive-off scenarios within WP2 Tasks 2.3 & 2.4 and reported on in D2.4 (EoL Test Methods) and D2.5 (Cost Modelling).

The production output expectations highlighted above in terms of traditional OEM ICE testing will be considered, coupled with the stack performance targets and manufacturing metrics defined within DIGIMAN Deliverable Report D2.1 Section 3.1 and 4.1.