A Burn-in test station for the ATLAS Tile-calorimeter low-voltage power supply transformer-coupled buck converters

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Abstract. The Tile Calorimeter (TileCal) is a sampling calorimeter that forms the central region of the hadronic calorimeter of the ATLAS experiment. This detector is to undergo its Phase-II upgrade during Long-Shutdown in preparation for the start of operation of the High Luminosity Large Hadron Collider. The TileCal phase-II upgrade consists of numerous elements such as the Low-Voltage Power Supplies (LVPS) which reside on-detector. A total of 256 LVPSs provide the TileCal on-detector electronics with +10 VDC power. They contain eight transformer-coupled buck converters (Bricks) among other electronics. Access to the Bricks is limited to only once per year due to their location within the inner-barrel. If a Brick experiences a failure it can be offline for up to a year resulting in the front-end electronics that it services being offline for this extended period as well. Therefore, the reliability of the Bricks is a key concern that needs to be addressed during their production. To this end, all Bricks will be required to undergo Burn-in testing. This testing is a form of accelerated aging which allows for the reduction of Brick early-life failures once installed on-detector.

1. Introduction

The TileCal is a sampling calorimeter that forms the central section of the Hadronic calorimeter of the ATLAS experiment [1]. It performs several critical functions within ATLAS such as the measurement and reconstruction of hadrons, jets, hadronic decays of τ-leptons, and missing transverse energy. It also contributes to muon identification and provides inputs to the Level 1 calorimeter trigger system. The sub-detector is located in the pseudorapidity region $|\eta| < 1.7$[1] and is partitioned into four barrel regions. Each barrel region consists of 64 wedge-shaped modules which cover $\triangle\phi \sim 0.1\,\mathrm{rad}$ and are composed of plastic scintillator tiles, functioning as the active media, inter-spaced by steel absorber plates. A Super Drawer (SD) housing the Front-End (FE) electronics is located inside the widest section of each TileCal Module. In the third quarter of 2027, the start of the operation of the High-Luminosity Large Hadron Collider is planned with a foreseen peak luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The resulting environment has necessitated the development of new electronics, both on- and off-detector, to ensure the

[1] The pseudorapidity (η) is defined in terms of the polar angle θ as $\eta = -ln\tan(\theta/2)$.

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Table 1. V8.4.2 Brick protection circuitry trip parameters.

Protection circuitry	Trip parameters
Over voltage protection	11.50 V - 12.00 V
Over current protection	10.24 A - 10.75 A
Over temperature protection	70 °C ≥

continued peak performance of the detector under high pileup conditions and increased radiation exposure. The development of these electronic components falls under the ATLAS TileCal Phase-II upgrade [2].

2. The Low-voltage power supply (LVPS)

The upgrade of the LVPS falls under the TileCal Phase-II upgrade. The LVPSs form the second stage of a three stage Low-Voltage (LV) system which provides LV power to the FE electronics of the TileCal. The first stage of the LV system resides off-detector and is comprised of Auxiliary boards, that provide on/off control of the individual Bricks within a Low Voltage Power Supply (LVPS), as well as 200 VDC power supplies. An LVPS, of which one is located on the end of every SD, is comprised of eight transformer-coupled buck converters (Bricks), an Embedded Local Monitoring Board (ELMB), an ELMB Mother Board (ELMB-MB), a fuse board, and a cooling plate to which the Bricks are affixed. The Bricks function to step down the 200 VDC power, received from the off-detector power supplies to 10 VDC. The 10 VDC power is then routed to point-of-load regulators located on the FE electronics which perform the final stepping down of the voltage [3].

3. Bricks

A Brick, of which there are 2048 within TileCal, provides a nominal output current of 2.3 A at 10 VDC. At the centre of its design is the LT1681 controller chip. It is a pulse width modulator that operates at a fundamental frequency of 300 kHz. The pulse width is controlled via two inputs, the first of which is a slow feedback path that monitors the feedback voltage with a bandwidth of approximately 1 kHz. The second input is a fast feedback path that monitors the current through the low-side transistor on the primary side. The LT1681 provides an output clock to the Field Effect Transformer (FET) drivers, which perform the switching on the primary side. The design utilizes synchronous switching, That is, both the high-side and low-side transistors turn on and conduct for the duration that the output clock is in the high state, and both are off when the clock is in the low state. When the FETs conduct, current flows through the primary windings of the transformer, which then transfers energy to the secondary windings. A buck converter is implemented on the secondary side of the transformer. The output side also contains an additional inductor-capacitor stage for the filtering of noise. Voltage feedback for controlling the output voltage is provided. The V8.4.2 brick utilizes the same protection circuitry implemented on previous iterations of the Brick. The purpose of this circuitry is to initiate a trip of the Brick if operating parameters exceed a specified range from nominal. The design utilizes three types of inbuilt protection circuitry, Over-Voltage Protection (OVP), Over-Current Protection (OCP), and Over-Temperature Protection (OTP). These circuits, if activated, initiated an immediate shutdown of the brick. Their activation depends on preset thresholds which are stated in Table 1. A trip should be initiated within the given thresholds for the OVP and OCP and above 70 °C for the OTP.

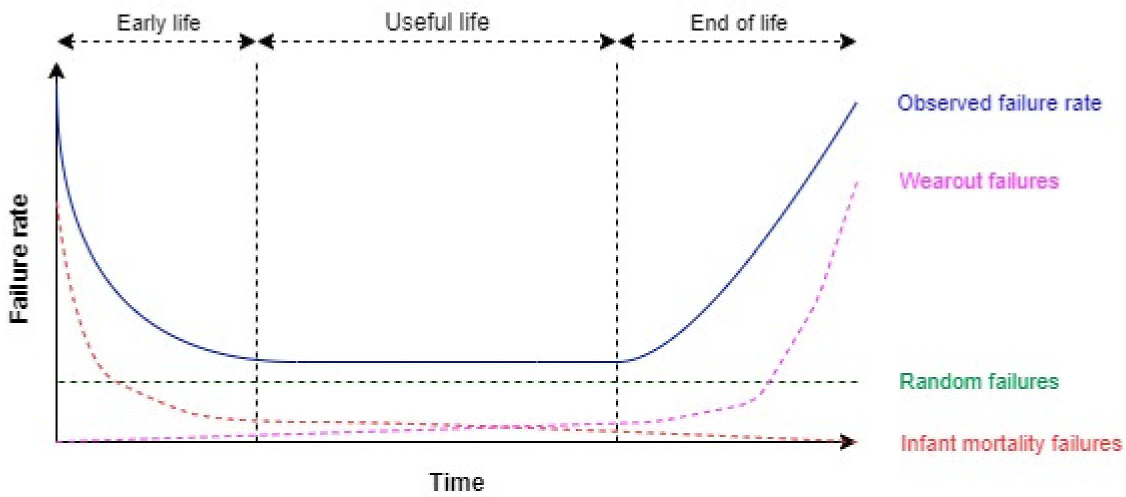

Figure 1. A generalized Bathtub-curve illustrating the failure rate as a function of time as experienced by electronic components.

4. Motivation for Burn-in testing

Access to the LVPS Bricks is of the order of once per year as they are located within the Inner-barrel of the ATLAS detector. Therefore, any Bricks which fail will result in a portion of the Module to which they provide power being offline for the same period of time. Due to this, the reliability of the Bricks is of the utmost importance. The Bricks failure rate and reliability are inversely proportional. This failure rate can be approximated by what is known as a generalized electronics Bathtub-curve which is illustrated in figure 1. We can observe the undesirable high failure rate within the Early-life (Infant-mortality) region. Failures experienced in this region are known as Early-life (Infant-mortality) failures. These failures occur due to unavoidable manufacturing inconsistencies at both the device and component levels as well as numerous other sources such as mechanical damage during transport. Burn-in testing serves to actively address the former sources of Early-life failure and in doing so improves the reliability of the Bricks once installed on-detector. This is achieved by artificially ageing the Bricks towards the more desirable Useful-life region. The accelerated aging causes Bricks that would fail during their Early-lifetime to fail during the Burn-in procedure thereby allowing for them to be repaired before installation. This results in the Brick population obeying an approximately constant failure rate from their time of installation as the Early-life failures have been screened out. A Burn-in station achieves the accelerated aging of the Bricks by implementing a Burn-in procedure.

Table 2. Preliminary Brick Burn-in parameters and nominal Brick operating parameters.[2]

Parameter	Burn-in	Nominal operation
Brick operating temperature	60° C	35° C
Applied load	5 A	2.3 A
Run-time	8 hours	-

5. The Burn-in procedure

The Burn-in procedure subjects the Bricks to sub-optimal operating conditions which function to stimulate failure mechanisms within the Bricks. These conditions need to fall within the

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extrema allowed for by the Brick design and operation. There are two reasons for this. The first of which is related to effective Burn-in and the second is related to the implementation of the Burn-in procedure. Firstly, the failure mechanisms stimulated must be of the kind that can be experienced during operation within TileCal. Inducing failures by the application of excessive operating conditions such as impossibly high loads serves no purpose. This as a these failures will not be due to due to unavoidable manufacturing inconsistencies but are rather a result of the Bricks being operated outside of their design specifications. The second reason for limiting the Burn-in parameters[1] provided in Table 2 to within the Bricks final operating extrema is due to the Bricks inbuilt protection circuitry. A Brick will initiate a trip if the OCP, OVP or OTP trip parameters are met. If the operating parameters are set to within the variance of the trip points maxima intermittent Brick trips would occur during the Burn-in procedure. Whereas, if the parameters are set higher than this variance the Bricks will start and immediately trip.

6. The Burn-in test station

The Burn-in station is of a fully custom design. This was necessitated by the unique design of the Bricks and also allows for the fine-tuning of the applied Burn-in parameters. It consists of six distinct elements namely the test-bed, hardware, cooling system, control software, custom PCB Programmable Integrated Circuit (PIC) firmware, and custom instrumentation drivers.

6.1. Test-bed

The Test-bed is primarily responsible for housing the Burn-in station electronic hardware, heat sinks, water manifolds (housed externally) and the 8 Bricks undergoing the burn-in procedure. Secondary roles include providing electrical and thermal insulation which function to provide a safety measure for the operators and to provide a temperature-controlled environment for the Bricks, respectively.

6.2. Hardware

The Burn-in station hardware is composed of a programmable DC power supply (BK precision XLN600-26), a PC, and custom Printed Circuit Boards (PCBs) as illustrated in figure 2. The custom electronic boards are subdivided into four types. These are the Main Board (MB), Brick-Interface (BI) board, Dummy-Load (DL) board, and the Dummy-load Interface (DI) board.

Mainboard: There is one MB per Burn-in station. It functions purely as a multiplexer to each individual interface board [4]. This allows the LabVIEW control software on the PC to communicate via UART to each individual PIC located on the interface boards.
Brick-interface boards: There are eight BI boards per Burn-in station with one associated with each of the Bricks undergoing the burn-in procedure. These boards provide control, digitization, and transmission functions to their respective Bricks. The control functions can be subdivided into two. The first function allows for the Brick to be powered on or off via the Tri-state signal line as in an LVPS. The second allows for the on/off control of the input 200 VDC provided to the Brick by the DC power supply. The BI board digitizes the analog behavioral parameter signals received from the Brick by use of a 16-bit analog-to-digital converter. These parameters are the input voltage, input current, output voltage, output current, and two temperatures. The now digitized signals are transmitted to the PC via the MB.
Dummy-load boards: A Burn-in station contains two DL boards with each containing four independent current loads which receive the output power from four Bricks. The output power is shunted through a MOSFET operating in the ohmic region thereby converting it to heat to be

[1] These are considered to be preliminary parameters as the Brick design has yet to be finalized due to pending radiation studies. Changes to the design of the Brick will impact the Burn-in parameters.

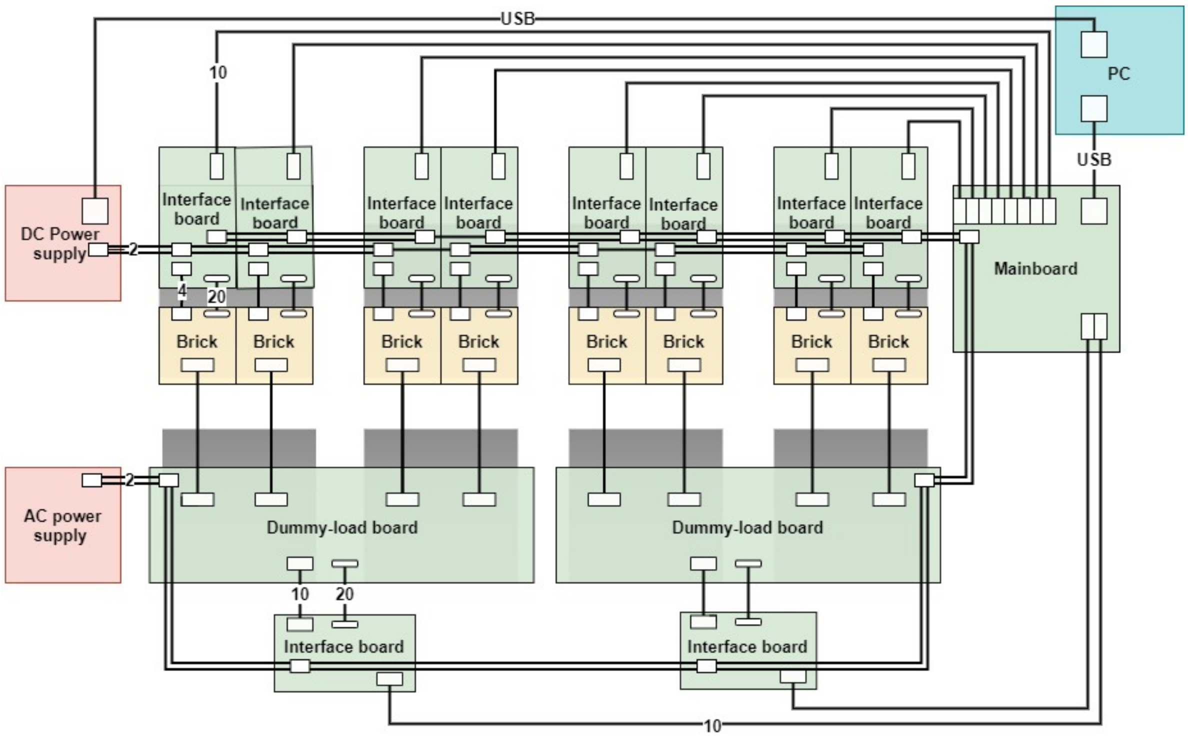

Figure 2. A block diagram of the Burn-in station hardware.

dissipated. The applied load to the Bricks is controllable allowing for the application of different loads if need be. This provides flexibility in the Burn-in station operation.

Dummy-load interface boards: There are two DI boards per Burn-in station, one per Dummy-load board. These interface boards provide control, digitization, and transmission functions to their associated Dummy-load board. An individual DI board is responsible for shifting bits into a digital-to-analog converter located on the DL board in order to control the load current applied to each of the four Bricks. The LI board digitizes the output Brick voltage and current sampled at the DL board. This is done for each of the four Bricks attached to the associated DL board.

6.3. Cooling system

Active cooling of the Burn-in station is required due to the presence of two heat sources within the test-bed. The first source consists of the 8 Bricks. Heat is generated by the Bricks as a result of the inefficiency of the step-down process. The second heat source consists of the two Dummy-Load boards which convert the output power received from the eight Bricks into heat. The heat produced by these two sources is sunk into water cooled plates which are identical to those within a TileCal LVPS. This replication of the cooling hardware, and in particular the cooling hardware which comes into contact with the Bricks, creates an identical thermal distribution throughout a Brick during Burn-in.

The cooling system topology consists of four independent cooling channels, arranged in parallel, each of which is composed of two cooling plates connected in series. The four Brick cooling plates comprise the first row of cooling plates. They receive the cooled water from the water-chiller via a 1-to-4 intake manifold. It is important that these cooling plates receive the coolant first. This as the temperature of the Bricks which is controlled by the water chiller is a key parameter of the Burn-in procedure. The intake coolant temperature can be calibrated to produce the desired Brick Burn-in operating temperature. The now warmer coolant flows to the second row of cooling plates. A single DL board has its four MOSFETs directly attached to two cooling plates in this row with the other DL board occupying the second pair of cooling plates. The now hot coolant merges into a 4-to-1 manifold after which it travels to the water chiller to be cooled and recirculated.

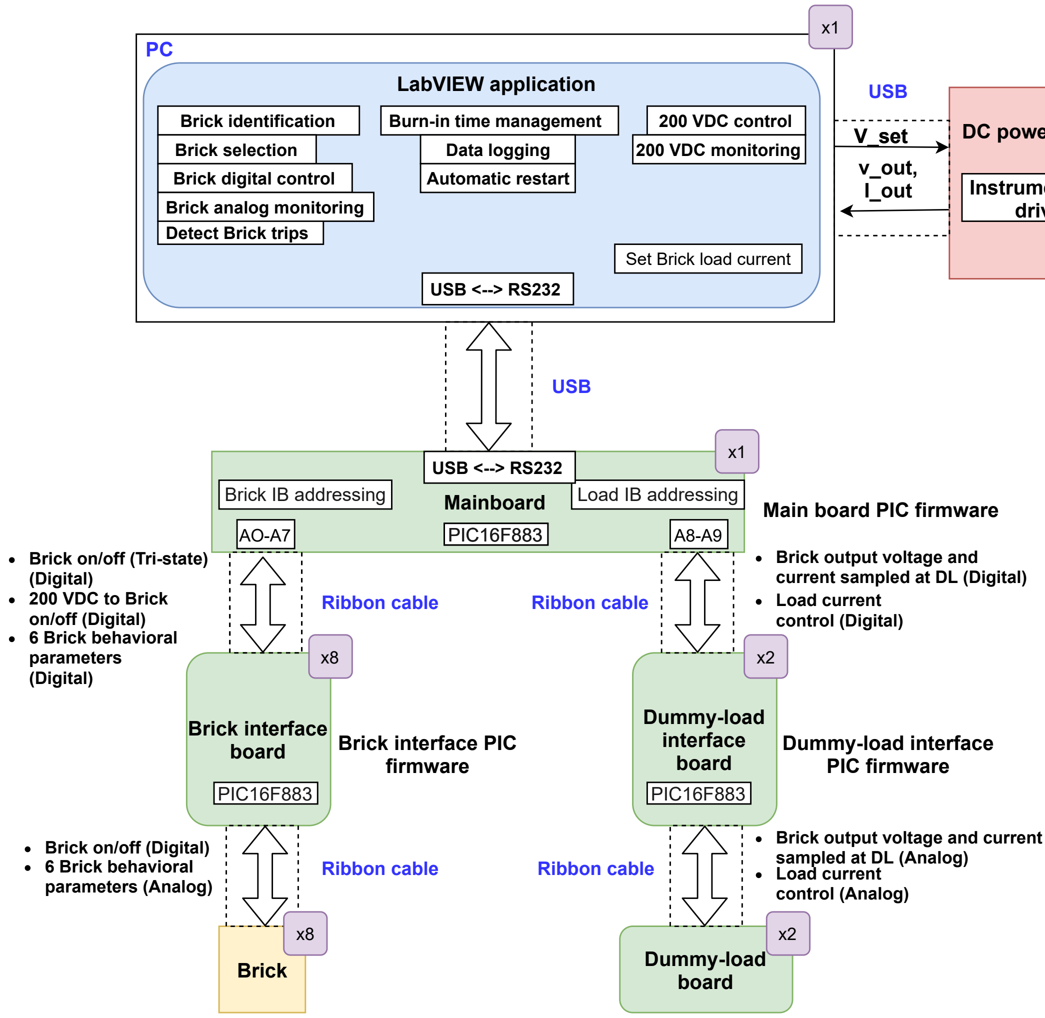

Figure 3. A simplified block diagram illustrating the Burn-in station data flow.

6.4. Software

The software required for the operation of a Burn-in station can be divided into three categories. These are the LabVIEW control and monitoring application, the PCBs (PIC) firmware, and high voltage power supply instrumentation drivers. The relationships between these three categories can be observed in figure 3.

LabVIEW application: A custom application for the Burn-in station has been developed utilizing the LabVIEW graphical development suit. This application provides control, monitoring, and data collection capabilities. It allows for the automated implementation of the Burn-in procedure with minimal input from the user.

PIC firmware: All of the Burn-in station PCBs, excluding the DL boards, make use of a PIC. The PIC (PIC16F883) is a microcontroller which has the capability to be programmed with customized firmware. The function of the PIC is determined by the specific firmware which is programmed which is dependant on the PCB type. Therefore, a Burn-in station requires specific firmware for the MD, BI board, and DI board. With the BI board a DI board containing a subset of firmware due to each of these PCBs possessing a unique address (AO-A7 and A8-A9 respectively).

Instrumentation driver: A custom LabView driver was also created to communicate with the DC power supply via the LabVIEW VISA communications layer, over Ethernet.

7. Burn-in station development status

Two Burn-in stations are currently undergoing construction. The Test-beds for both stations have been completed with the cooling system having been fully commissioned. The hardware for the first station is currently undergoing testing before its installation within a Test-bed. The control software is the final outstanding deliverable and is in an advanced state of development.

8. Conclusions

The context of TileCal LVPS Brick Phase-II upgrade was provided with a detailed circuit overview of an LVPS Bricks also having been covered. An emphasis was placed on the Bricks in-built protection circuitry and the associated trip parameters. The motivation for and application of Burn-in testing was discussed in detail. This was followed by a concise breakdown of the Burn-in station hardware and software required to implement the Burn-in procedure. The proceedings then culminated with the current Burn-in station development status.

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