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Bake-Out Mobile Controls for Large Vacuum Systems

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Abstract
Large vacuum systems at CERN (Large Hadron Collider - LHC, Low Energy Ion Rings - LEIR...) require bake-out to achieve ultra-high vacuum specifications. The bake-out cycle is used to decrease the outgassing rate of the vacuum vessel and to activate the Non-Evaporable Getter (NEG) thin film. Bake-out control is a Proportional-Integral-Derivative (PID) regulation with complex recipes, interlocks and troubleshooting management and remote control. It is based on mobile Programmable Logic Controller (PLC) cabinets, fieldbus network and Supervisory Control and Data Acquisition (SCADA) application. The CERN vacuum installations include more than 7 km of baked vessels; using mobile cabinets reduces considerably the cost of the control system. The cabinets are installed close to the vacuum vessels during the time of the bake-out cycle. Mobile cabinets can be used in any of the CERN vacuum facilities. Remote control is provided through a fieldbus network and a SCADA application

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Large vacuum systems at CERN (Large Hadron Collider - LHC, Low Energy Ion Rings - LEIR...) require bake-out to achieve ultra-high vacuum specifications. The bake-out cycle is used to decrease the outgassing rate of the vacuum vessel and to activate the Non-Evaporable Getter (NEG) thin film. Bake-out control is a Proportional-Integral-Derivative (PID) regulation with complex recipes, interlocks and troubleshooting management and remote control. It is based on mobile Programmable Logic Controller (PLC) cabinets, fieldbus network and Supervisory Control and Data Acquisition (SCADA) application. The CERN vacuum installations include more than 7 km of baked vessels; using mobile cabinets reduces considerably the cost of the control system. The cabinets are installed close to the vacuum vessels during the time of the bake-out cycle. Mobile cabinets can be used in any of the CERN vacuum facilities. Remote control is provided through a fieldbus network and a SCADA application.

INTRODUCTION

Why do Vacuum Systems need bake-out?

CERN Accelerators have more than 7 km of beam vacuum vessels, which operate at room temperature and require Ultra-High Vacuum (pressure under 1.10^{-10} mbar). During installation or after a vacuum intervention, the vessels require conditioning; this consists of a heating cycle (bake-out) over several days, with a dual role:

- A fast and large outgassing of the vacuum vessels: after the bake-out, vacuum vessels must have significantly reduced their outgassing rate.
- A thermal activation of the Non Evaporable Getter (NEG): the oxide layer present at the NEG surface is dissolved releasing a high pumping speed thin film [1].

The bake-out control system was first developed in 2006, for the installation of the LHC and its experiments [2]. It has been upgraded in 2013 for the vacuum interventions of the Long Shutdown (2013 - 14).

SPECIFICATIONS

The specifications were defined in collaboration with the vacuum teams in charge of the bake-out operation.

The main characteristics of the Bake-out controls are:

- MOBILITY: considering that bake-out cycles are non-recurrent, short in duration (4 days in average), and take place in very different locations, the local control cabinet must be mobile. This reduces substantially the global number of required cabinets.
- THERMAL REGULATION: the control cabinet has to regulate a wide variety of heating systems, with very different thermal properties. Pre-defined recipes shall be available to adjust the temperature set-points of the complex thermal cycle required for the NEG activation.
- DIAGNOSTICS AND ERROR MANAGEMENT: Bake-out is a critical process. Over-temperature may damage components of the accelerator. Reliable diagnostics and error management are required.
- LOCAL CONTROL: a touch panel shall be added to the cabinet. Operators shall be able to locally set-up the Bake-out control parameters.
- REMOTE CONTROL AND LOGGING: the Supervisory Control And Data Acquisition (SCADA) application for vacuum systems shall include remote control and data logging for the Bake-out cabinets.

HARDWARE DESIGN

The bake-out cabinet is a CERN design based on Siemens® Programmable Logical Controllers (PLC) S7-300 series, comprising a CPU, Input/Output modules, Profibus® and Ethernet interfaces (Figure 1).

Figure 1: Bake-out mobile cabinet

In the accelerators tunnel, the bake-out cabinets are connected to the master PLC via the Profibus® interface. The master PLC is a gateway to the SCADA server.

In labs or test stands, the bake-out cabinets will be connectable directly to the SCADA server, through the Ethernet interface (software still to be developed).

The ON/OFF regulation uses solid state power relays. The maximum commutation frequency is limited by the PLC software to 5 Hz.

The bake-out cabinet has 24 “regulation channels”. Several heaters can be connected to the same regulation channel, up to a maximum of 4 kW; one temperature sensor must be provided for each regulation channel. The maximum total power of all the heaters of a cabinet is 44 kW. This configuration offers a good compromise between the number of cabinets and the length of cables for complex and widely-spread vacuum systems. The bake-out cabinet has also 8 “control channels”; a temperature sensor can be connected to a control channel to be used as an interlock on regulation channel.

The bake-out cabinet is locally parameterised by the user, on a dedicated touch panel.

Two remotely controlled circuit breakers supply the power relays. The circuit breakers can be remotely switched off in case of critical bake-out error.

All these functionalities are integrated in a standard 13-unit high and 19 inch width rack, mounted on wheels.

A total of 88 bake-out control cabinets have been manufactured.

Fieldbus networks (Profibus®), dedicated to mobile pumping groups and mobile bake-out cabinets, are installed in several CERN accelerators. In the LHC warm sections (Figure 2), Profibus sockets are available every 15 m. Before starting a bake-out cycle, the mobile cabinet is connected to the fieldbus. The bake-out cycle can then be monitored by the vacuum SCADA application.

Figure 2: Bake-out mobile cabinet in the LHC Tunnel

PLC SOFTWARE

Regulation and recipes

The thermal regulation is based on a Proportional-Integral-Derivative (PID) regulation (Figure 3).

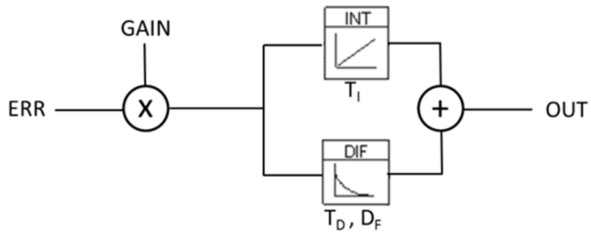

Figure 3: PID Regulation algorithm

The PLC software integrates the Siemens® PID Control Function block called "TCONT_CP" [3]. This function is a temperature controller block with continuous input signals and pulsed digital outputs, and includes a self-tuning function for the PID parameters. Its step response in the time domain is:

$$\boldsymbol{OUT(t) = GAIN * ERR\left(1 + \frac{1}{T_I} * t + D_F * e^{-\frac{t}{T_D} * D_F}\right)}$$

Where *OUT(t)* is the manipulated output variable in automatic mode of the controller; *ERR* is the step change of the normalized error (i.e. the relative difference between set-point and process variable); *GAIN* is the controller gain; T_I is the integral time constant (seconds); T_D is the derivative time constant(seconds); D_F is the derivative factor.

Default PID parameters values are used for standard bake-out cycles (*GAIN*= 20; $T_I = \infty$, i.e. integral disabled; and $T_D = 0$ s, i.e. derivative disabled). If the chamber being baked-out has specific thermal properties, the PID parameters shall be manually entered by the operator or auto-tuned by the PLC. To avoid any regulation incident due to incorrect PID parameters, they are reset to the default values after a restart of the PLC; furthermore, this reset requires the operator’s confirmation.

To suppress any small-amplitude steady oscillation, a dead-band is applied to the error signal. When the temperature set-point is modified, the PID regulator is automatically re-initialized.

The complex temperature cycles may require up to 12 pre-defined recipes. For any other specific cycles, operators are able to customize the recipe for each channel.

Diagnostics and error management

A LHC standard vacuum sector (50 m long) has around 150 heaters, installed permanently or temporary. The number of sensors, cables and connectors has been reduced in order to save material. There is an average of 3 heaters per temperature sensor, and therefore per regulation channel. Consequently, those 150 heaters can be regulated using only 2 cabinets (48 channels).

One drawback of having several heaters sharing one thermometer is that: in case of failure of the main heater (the one with thermometer), the other heaters may reach a temperature much higher than the set-point, while the sensor is still much cooler, due to the slow thermal conduction.

To address this situation, the difference between the set-point and the sensor reading (ΔT in Figure 4) is monitored; warnings are issued if it exceeds 15 or 25 ^{o}C; above 50 ^{o}C, the channel, or even all the channels, are stopped (depending on the chosen safety level).

Another example of over-heating may happen if the sensor has not a good thermal contact with the material being heated. In such a case, the PID may keep the associated heaters at full power for a long time.

To avoid material damage, and depending on the safety level, after 10 min of full power a warning is issued, or the channel is stopped, or even all channels in the cabinet.

Critical or fragile components such as beam instrumentation or detector chambers are also baked. Additional safety features were developed for these:

- Operators can limit the maximum power delivered to the heaters.
- Any of the new "control channels" can be used as interlock for a regulation channel. In case of temperature overshoot, and depending on the safety level, the channel is stopped, or even the power of the whole cabinet is shut down by remotely controlled circuit breakers.

Troubles and unexpected events are classified from "warning" level (minor events, no action needed) to "critical error" level (major events, with actions needed). A regulation channel has 5 warning status, 2 error status, 1 critical error status and 3 user-defined (warning, error, and critical-error) status.

Operators can define the safety level according to the severity of the bake-out process. Figure 4 lists the resulting actions in case of an error.

<table>
<tr><th rowspan="2">Channel Status (Error Code)</th><th colspan="4">ACTIONS</th></tr>
<tr><th>SAFETY LEVEL 1</th><th>SAFETY LEVEL 2</th><th>SAFETY LEVEL 3</th><th>SAFETY LEVEL 4</th></tr>
<tr><td>OK</td><td colspan="4">No Error/Warning, no action</td></tr>
<tr><td>Output calculated power = 0%</td><td colspan="4" rowspan="6">Warning, no action</td></tr>
<tr><td>Output calculated power = 100%</td></tr>
<tr><td>Warning from control channel (control sensor overshoot warning threshold)</td></tr>
<tr><td>ΔT > 15°C</td></tr>
<tr><td>ΔT > 25°C</td></tr>
<tr><td>Regulation sensor open cable</td><td colspan="4" rowspan="2">ERROR, STOP CHANNEL</td></tr>
<tr><td>Interlock from control channel (control sensor overshoot error threshold)</td></tr>
<tr><td>Output calculated Power= 100% longer than 10 minutes</td><td>Warning</td><td colspan="2"></td><td></td></tr>
<tr><td>Interlock from control channel remaining even after channel stopped</td><td colspan="2" rowspan="2"></td><td colspan="2" rowspan="3">CRITICAL ERROR, SHUT DOWN ALL POWER RELAYS</td></tr>
<tr><td>ΔT > 50°C</td></tr>
<tr><td>External digital input interlock</td><td colspan="2"></td></tr>
</table>

Figure 4: Errors management

Communication between cabinet & Master-PLC

14 fieldbuses for mobile controllers have been installed in all CERN Accelerators. Every one of the 88 mobile bake-out cabinets can be connected to any of the fieldbuses. However, the maximum number of cabinets connected together on the same fieldbus usually does not exceed 15. In order to spare fieldbus addresses in the master PLC, only 20 slots have been reserved for bake-out. A communication protocol has been defined to automatically allocate one of these slots to a cabinet when it connects to the fieldbus.

The presence of equipment on the fieldbus is analysed by the Master PLC. When a new hardware connection is detected, the Master PLC sends a 'Handshake' message with a handshake number. The bake-out cabinet sends his equipment type and position (entered by the operator on the touch panel), and then continuously sends process data (channels status, process values and set-points). As absolute time is not critical for bake-out process, the data is not time stamped on the cabinet, but only on the SCADA at reception.

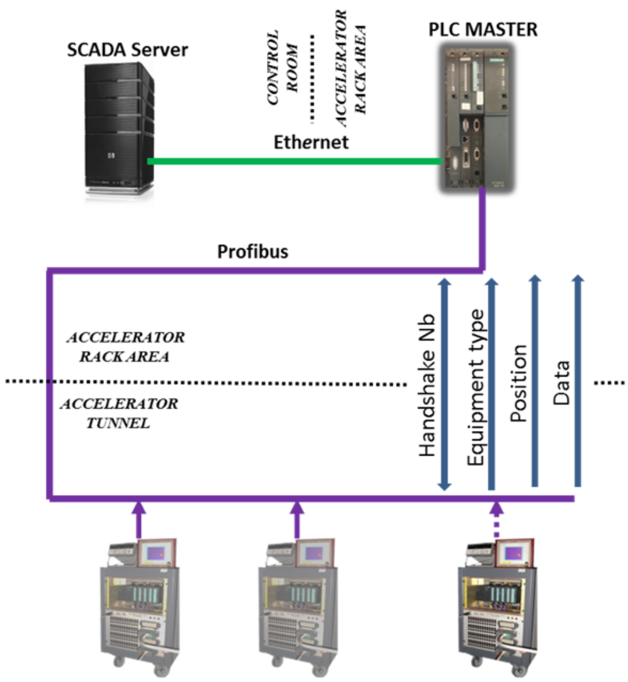

Figure 5: Mobile Controllers Fieldbus

SCADA APPLICATION

The SCADA vacuum application [4] includes several bake-out features:

- Status Panel: real time status (state, process value, set-point value, and safety level) is shown for each bake-out channel. This information is sorted by vacuum sectors and bake-out cabinets (Figure 6).

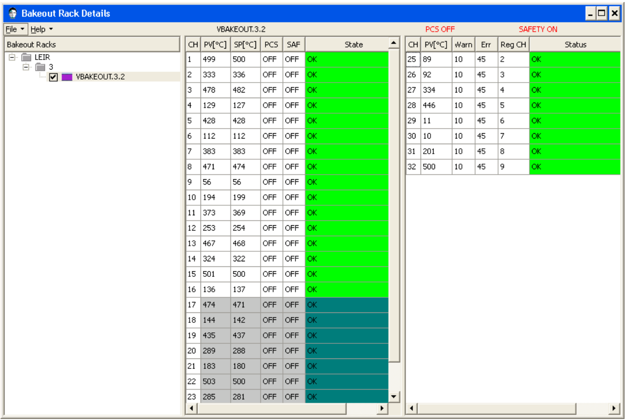

Figure 6: Status Panel

- History Panel: process values, set-points and vacuum-sector pressures can be shown in a same graph and so operators can follow the correlation between temperatures and pressures, and notice any unusual behavior (Figure 7).

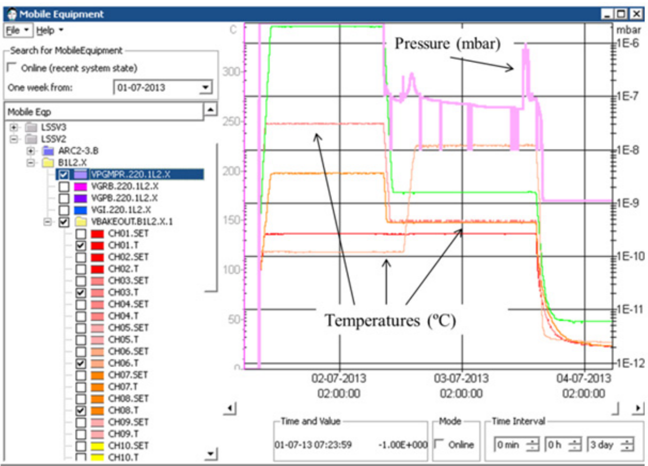

Figure 7: History Panel

- Notifications: the SCADA has a generic e-mail/SMS messaging system. It can be parameterized to notify operators in case of bake-out channel error.

CONCLUSION

More than 160 bake-out cycles have been foreseen for the 2013-2014 CERN accelerators long shutdown. The new application for bake-out control has been used during the 30 cycles already performed. This new application has improved: the safety, the regulation accuracy and the parameters set-up time. The remote monitoring access allows post-mortem diagnostics, logging for follow-up reports and error notifications.

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