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CERN experience and strategy for the maintenance of cryogenic plants and distribution systems

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Abstract. CERN operates and maintains the world largest cryogenic infrastructure ranging from ageing installations feeding detectors, test facilities and general services, to the state-of-the-art cryogenic system serving the flagship LHC machine complex. After several years of exploitation of a wide range of cryogenic installations and in particular following the last two years major shutdown to maintain and consolidate the LHC machine, we have analysed and reviewed the maintenance activities to implement an efficient and reliable exploitation of the installations. We report the results, statistics and lessons learned on the maintenance activities performed and in particular the required consolidations and major overhauling, the organization, management and methodologies implemented.

1. Introduction

CERN is the European Organization for Nuclear Research located on the French-Swiss border near Geneva. Its mission is to enable international collaboration in the field of high-energy particle physics research and to this end it designs, builds and operates particle accelerators, the associated experimental areas and various test facilities for the main components. The flagship of this complex is the Large Hadron Collider (LHC).

Particle accelerators, detectors, experimental areas and test facilities are largely based on superconducting technology [1] and therefore require significant - in size and complexity - cryogenic systems to produce and distribute efficiently and reliably the cooling power required to maintain superconducting devices at their nominal operating temperatures and rapidly recover from any disturbances.

CERN has been operating cryogenic installations for several decades and adapted and improved since then the operation and maintenance activities [2]. The start of operation of the LHC and its large cryogenic system has significantly increased the number and geographical location of equipment and components. The stringent requirements in operational availability and reliability for physics have underlined the importance and impact on performances and costs of maintenance activities and spares management.

CERN has implemented a Computer Aided Maintenance Management System (CAMMS) in 2009 with the start of the LHC operation. The data collected so far have allowed to review, adapt and optimize



the maintenance activities to efficiently improve the exploitation of the installations and increase the availability of the machines for the research and physics programs.

2. CERN cryogenic infrastructure

CERN's installations are located on the ground and in underground caverns and tunnels and distributed over a radius of about 4 km centered on one of the two main sites (Preessin site) and over the French - Swiss border as shown in figure 1.

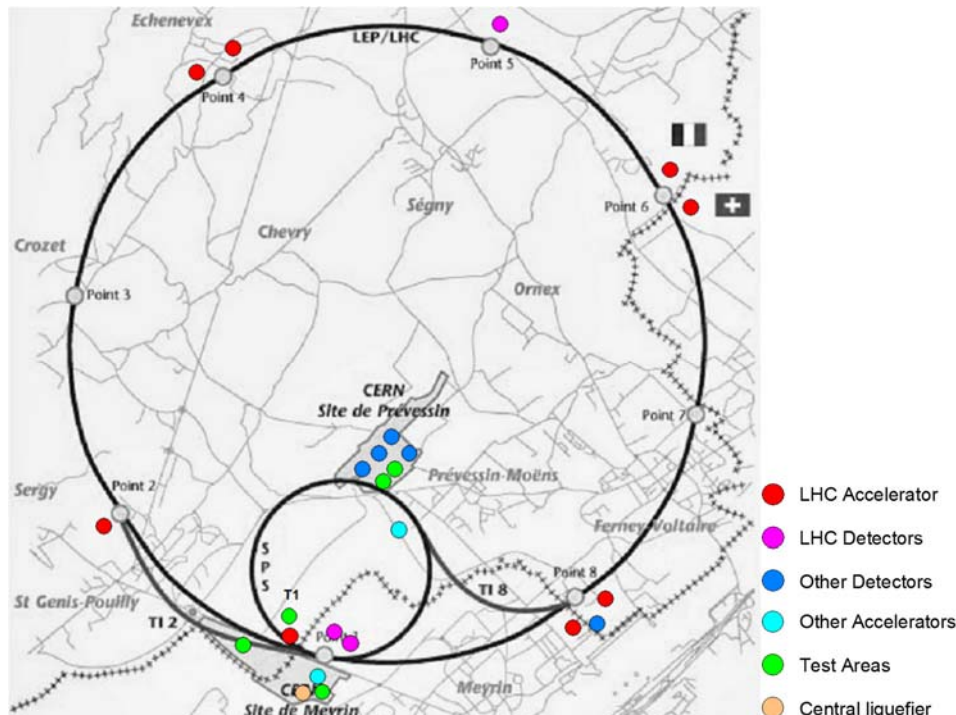


Figure 1. Plan of the CERN site and location of the main cryogenic installations.

The cryogenic installations and equipment are mainly based on state-of-the art industrial components developed with industry over the years and older installations consolidated and upgraded as required according to the physics and research program evolution. The installations comprise also very specific low temperature components and operate with various cryogenic fluids (LHe, LN₂, LAr, LKr). The main type and size are presented in figure 2 and provide cooling to the following cryogenic users: the LHC accelerator and its detectors, other accelerators and detectors, the test areas infrastructures and the central helium liquefier. The present total helium cryogenic refrigeration capacity well exceed 160 kW @ 4.5 K and more than 20 kW @ 1.9 K, distributed over a total integrated length of about 30 km.

The largest installation and equipment can be found in the LHC complex [2] to provide cooling of 27 km of superconducting magnets operating at 8.3 T in a superfluid helium bath at 1.9 K. It consists of eight pairs of cryogenic plants of 18 kW @ 4.5 K and 2.4 kW @ 1.9 K serving each 3.3 km long sectors via compound cryogenic distribution lines as well as the associated infrastructure to manage an inventory of more than 150 t of helium and a distribution of more than 10'000 t of nitrogen per year. The LHC has also two large superconducting magnets detectors, ATLAS and CMS, with 3 dedicated helium refrigerators for a total capacity of 10.3 kW @ 4.5 K as well as a nitrogen refrigerator.

There are more than 20 cryogenic areas around the CERN site and a total of about 40'000 inventoried parts divided in 4 classes of components (mechanical, electrical, instrumentation and vacuum) and 25 main types of equipment (adsorber, filters, turbines, valves, motors, measurement devices, pumps, etc.).

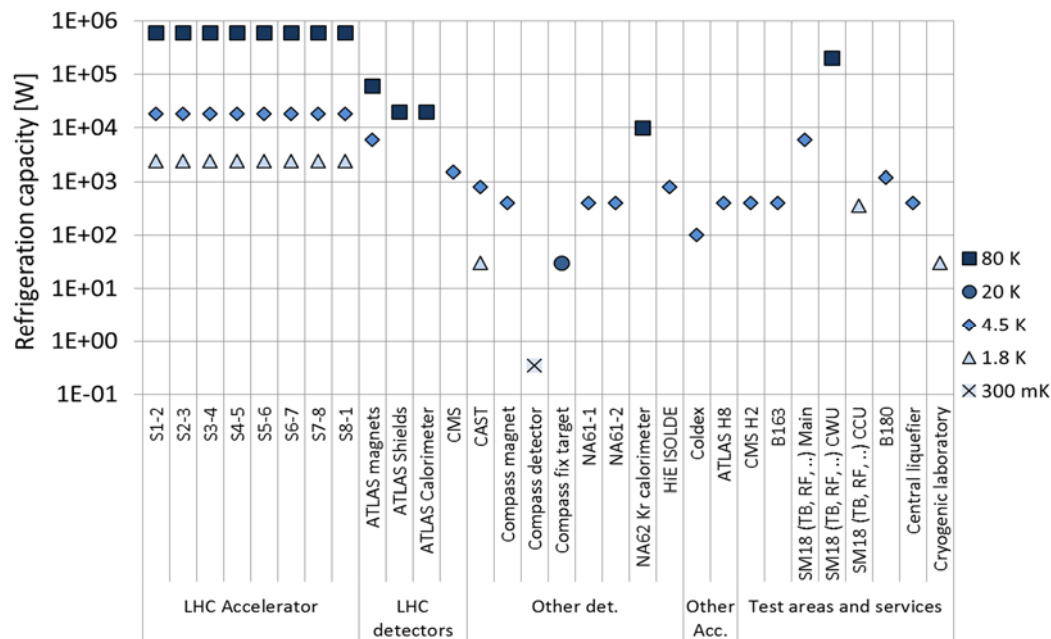


Figure 2. Cryogenic installations and refrigeration capacity at various temperature levels.

3. Exploitation of the cryogenic infrastructure

CERN's installations are continuously operated over the year by CERN's staff with the support of industrial contractors for routine operation and maintenance (preventive, corrective and spare parts management). There are only few short technical stops for critical corrective maintenance interventions. Preventive maintenance is performed either during one month yearly shutdowns, or every four to five years during major year-long shutdowns, depending on the type of installations and the organization research program.

An effective maintenance program has been progressively implemented for the LHC, and retroactively for all the other installations, with the support of the Computer Aided Maintenance Management System Infor EAM™. It consists of the following main phases:

- Assets inventory and management
- Maintenance Procedures and documentation management
- Spare parts analysis and management
- Work management and administration
- Work control and optimization
- Implementation and analysis of Key Performance Indicators

A comprehensive analysis to define the required maintenance activities, inclusive of the spare parts needed for the corrective interventions, is usually based on the functional and Failure Mode Effects and Criticality Analysis of the system taking into account the machine requirements and the manufacturer documentation and recommendation. Nevertheless, in particular for older plants, an analysis at posteriori of operation and maintenance data, events numbers and causes ranked by occurrence and criticality, allows to obtain sufficiently good information to establish (if not existing) or reviewing the maintenance and spare parts management program.

For strategic reasons CERN has implemented since 1994 partnership with industrial contractors to perform the maintenance of its cryogenic infrastructure. The latest contract running since 2009 is based on the maintenance of the installations and management of the spare parts under task oriented obligations. Major overhauling of motor and compressors, maintenance of specific non industrial components or key expert advice (e.g. vibration analysis) and consolidation or upgrade of the equipment are executed via separate industrial contracts or directly performed by CERN's personnel.

The contractor services executed under Infor EAM™ consist in:

- Regular inspections of the plant(s) condition according to the inspection plan;
- Corrective maintenance;
- Preventive maintenance according to the maintenance plan and agreed schedule;
- Asset management comprising: management of the maintenance documentation, management of the equipment database, updates and elaboration of inspection and maintenance plans;
- Work order management;
- Spare part management comprising: management of the existing spare part stock, management of consumables, spare part procurement;
- Quality Assurance and Control,
- Monitoring of the performance of maintenance activities to optimize plants availability, reliability and cost.

CERN oversees and inspects the activities and, reviewing the Key Performance Indicators agreed with the contractor, provides general guidance, implements strategic decisions, requests and approves modification of the maintenance plans and spare parts stocks.

There are no CERN staff maintenance dedicated resources. Three part-time staff monitor and guide the work of twenty full-time equivalent contractors performing the maintenance baseline activities (i.e. corrective scheduled interventions or on-call emergencies and light preventive) and spare parts management work during non-shutdown periods. The contractor resources are increased to over 30 during major year-long shutdowns.

4. Maintenance experience

The use of cryogenics at CERN originated in the 1960s but, it is only in the last decade that, due to the increase in size and complexity CERN has progressively implemented a Computer Aided Maintenance Management System originally based on tracking spares parts transactions and intervention via simple databases and now evolved into a comprehensive and effective maintenance management program based on Infor EAM™.

The largest cryogenic infrastructure serving the LHC machine started in 2009 and went through a full cycle of operation, short technical stops and a major shutdown of two years to consolidate the machine and perform all required preventive maintenance activities. This has allowed to collect a significant amount of data to analyze and review the maintenance methodology, the maintenance plans, the required spare parts and finally improve the reliability and availability of the cryogenic system.

4.1. Maintenance methodology

A large amount of work is required to perform the full inventory, classification and upload in the database:

- the system assets with the related documentation and technical information (technical characteristics, manufacturer, dates, serial number, drawings, operation and maintenance documentation)
- the maintenance plans (preventive work with the required information on the work instructions, periodicity and required spares)
- the maintenance work instructions (i.e. corrective activities) and critical spares type and quantities
- the monitoring tasks (inspections, checklists, etc.).

Ideally this is performed during the closure of the project construction phase but it nevertheless requires continuous update throughout the lifetime of the equipment.

The work execution is managed in the CAMMS via a system of Work Orders (WO) containing all required information (type, required spares, scheduled intervention time, resources, related documentation, etc.) and executed through a defined sequence of acceptance, review and approval steps.

The preventive maintenance WOs are automatically issued and planned by the CAMMS based on the maintenance plan information (time or operating hours).

The work control and improvement system is based on Key Performance Indicators that allows not only to oversee the contractor work but also monitor the maintenance plan performances and spare parts usage and criticality.

The main KPIs (fully or partially implemented in the CAMMS) used to date are (total, per installation, per geographical location, per technical trade):

- preventive maintenance hours and costs
- corrective maintenance hours and costs
- ratio of corrective over preventive maintenance hours and costs
- inspection hours and costs
- spares and consumables transactions and minimum quantities alert
- number of open / closed Work Orders and resources usage
- maintenance work quality (based on the number of WOs re-opened on the same asset)
- maintenance work delivery (based on the WOs re-scheduled or delayed)
- Earn Value Management on preventive maintenance programs (planned and actual cost)
- Number of accidents and near misses

In addition CERN personnel performs additional controls and verifications during or after an intervention to audit safety, quality, and execution time and spares transactions.

4.2. The LHC Long Shutdown 1

The LHC first long shutdown (so called LS1) took place between 2013 and 2014 after more than three years of continuous operation, and more than 40'000 cumulated running hours on each installation, leading to the discovery of the Higgs particle. The time and duration were chosen in order to acquire sufficient physics data from the LHC detectors, perform the required magnets interconnections consolidations before a further increase in the collision energy, execute the preventive maintenance of all cryogenic equipment and the major overhauling of rotating machinery.

About 4400 maintenance plans, based on the original data entered in the CAMMS, were activated and implemented via the generation of the corresponding WOs. All the corrective maintenance WOs that were not critical and therefore not executed during the run, in order to limit the machine downtime, were also added. The preparatory work to review and plan the activities took a full year to optimize the resources available and review in detail and adapt to the reality of the field the activities theoretically defined in the CAMMS. At the end of the exercise more than 5000 WOs were accepted and executed.

The required spares were identified by the CAMMS via an exhaustive Bill of Materials to optimize number and type as well as exhaustively document components and parts in the CAMMS. The final list of spares was then ordered in anticipation of the work execution to avoid last minute delays during the shutdown and smoothen over a longer period the activities. The type and quantities of the main spares, consumables and fluids used during the shutdown is presented in table 1.

The necessary additional resources to cope with all the planned activities were recruited by the contractor to be able to perform the whole activities within an 18-month period.

The size and complexity of the maintenance activities for a major shutdown of this size not only confirmed the absolute need of a CAMMS and the use of adequate project tools (EVM, KPIs) to monitor and coordinate the large amount of activities and resources but also the necessity of Quality Control inspectors to minimize the amount of re-work and subsequent delays or under performances.

A large amount of work, summarized in table 2, was performed within a tight schedule organized around the main LHC machine consolidation work. In addition several helium storage pressure vessels (fifty-eight 250 m³ and sixty-eight 80 m³) required the regulatory decennial requalification. This was performed using a transportable piston compressor and applying the acoustic emission method.

Despite the large number of activities there was no major accident or technical fault jeopardizing the re-start of the operation of the machine.

Table 1. Main LS1 LHC spares, consumables, oil, types and quantities

type	quantity	unit
Joints O-ring	3769	pc
Other joints	2919	pc
Filtration cartridges	613	pc
Oil filters	311	pc
Couplings greasing kits	154	pc
Signal transducers	146	pc
Temperature sensors	35	pc
Maintenance kits pumps	47	pc
Activated charcoal	22040	kg
Compressors Breox® oil	16250	l
Pumps oil	919	l
Cleaning acid	1625	l
Solvent	139	l

Table 2. Main LS1 maintenance work

type	quantity	unit
<u>Major overhauling</u>		pc
Screw compressors	57	pc
Oil pumps	27	pc
Electrical motors	81	pc
Electrical motors (replaced)	33	pc
<u>Mechanical</u>		pc
Safety valves revision and test	2000	pc
Coalescers inspected	94	pc
Adsorbers treated	12	pc
Chemical cleaning	28	pc
<u>Instrumentation inspections and revisions</u>		pc
Valves	288	pc
Sensors	2000	pc
Transducers	3500	pc
<u>Vacuum</u>		pc
Pumps revision	200	pc
Gauges revision	235	pc
Vacuum valves revision	29	pc

It must however be noted that the following additional activities were required after inspection or following unresolved corrective WOs:

- The major overhauling (performed every 40'000 hours) of the motors and compressors showed, in addition to the normal wear, some damage and marking on rotating and fixed parts probably due to insufficient lubrication and metallic particles
- A normal general wear of the coalescers but a marked sensitivity of the overall separation efficiency to the correct installation and original make
- Some damage on the filters and particles (charcoal) accumulation

- An extended and comprehensive inspection of all filters to identify the origin of any abnormal quantity and type of particles
- The required replacement of the Rh/Fe and Germanium temperature sensors
- An extensive campaign of preventive maintenance on the cryogenic valves
- Several interventions on large valves in-line leaks and leaking joints

On the contrary the extent of instrumentation inspection, revision and calibration was significantly reduced by limiting the work to what was either identified, by the operation team, as required corrective actions or to sensors and transducers part of safety related control and acquisition channels.

4.3. Review of the LHC maintenance activities over the last five years

The LHC maintenance activities performed over the last five years are summarised in table 3. Maintenance costs (excluding major overhauls amounting to about 4 % of the compressors capital cost per year of operation) are presented in figure 3 showing the average corrective and light preventive maintenance costs (in % of the capital cost) over the years (2013 and 2014 cover the preventive maintenance of LS1). Despite the technological complexity of the LHC cryogenic system the overall ratio of corrective over preventive maintenance (based on cost) is homogeneously distributed over different installations and appears in line with industrial standards for more conventional equipment.

The LHC cryogenic system availability over 95 % during the past years of operation demonstrate that the maintenance activities were sound. With the re-start of the operation in 2015 it appears that the corrective maintenance could be further optimized leading to even higher availability figures.

Table 3. LHC Corrective and Preventive maintenance data 2011 - 2014

	Operation C/P	LS1 C/P	Total C/P	Mechanical C P	Elect/ Instr C P	Vacuum C P
Machine	23 %	8 %	13 %	20 % 40 %	30 % 14 %	5 % 3 %
ATLAS	15 %	13 %	14 %	8 % 12 %	10 % 6 %	2 % 1 %
CMS	25 %	3 %	13 %	8 % 13 %	15 % 10 %	2 % 1 %

4.4. Spare parts management

The spares cost distribution over the whole exploitation (operation and maintenance) period is shown in figure 4 in % of the capital cost. A significant amount is allocated to the preventive maintenance activities and the purchase to implement the minimal quantities according to a qualitative evaluation of the needs and risks. The cost of spares for preventive and corrective maintenance amounts to less than 0.1 % of the capital cost of the installations per year excluding major overhauling spares.

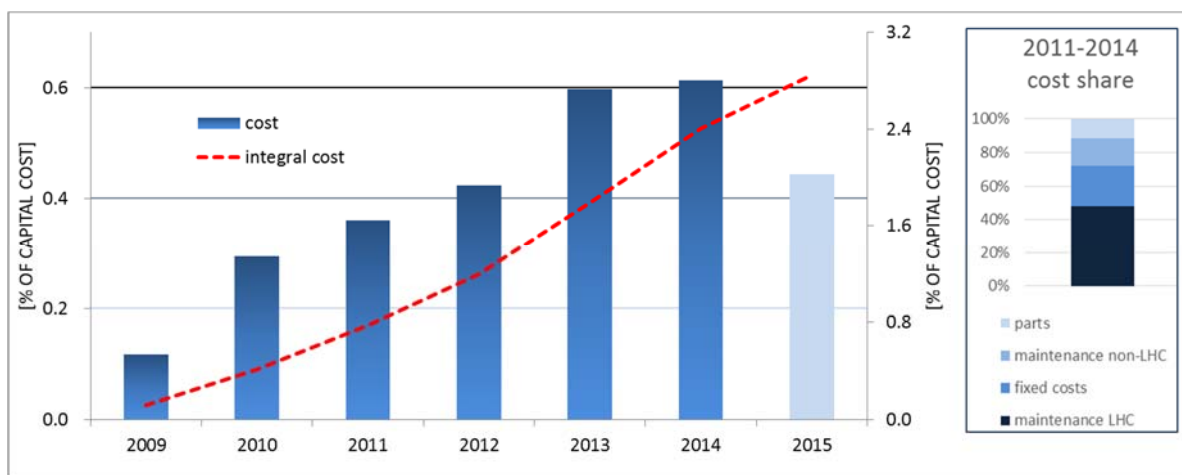


Figure 3. History of corrective and preventive maintenance for the LHC.

Based on the analysis of data during the exploitation of the installations we have now introduced a continuous review of the required spares to improve and optimize inventory (types and quantities) while guaranteeing the minimal spares during operational runs.

This is accomplished drawing a criticality matrix based on frequency, number and type of used spares, procurement delays, detectability of the fault, installed quantities and cost. Finally the results are reviewed and optimized via a Pareto analysis of the most used spares and a continuous review of the type and quantities effectively procured.

This is an iterative process linked to the ageing of the installations and the continuous review and adaptation of the maintenance plans.

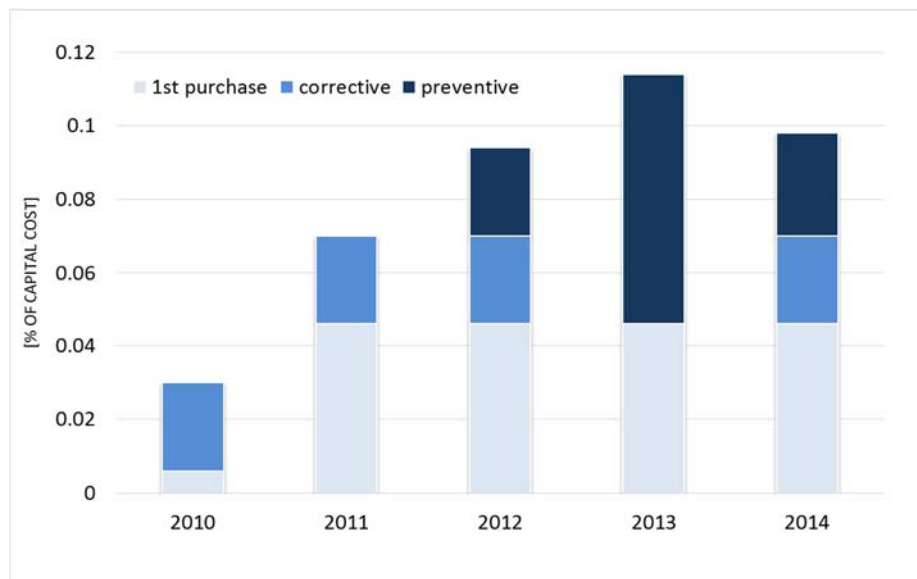


Figure 4. Cryogenics spares cost distribution over the years and type of usage.

5. Conclusions

CERN has accumulated over the years a significant amount of data and expertise in the maintenance and operation of large cryogenic plants and distribution systems. Key Performance Indicators show that most of installations and in particular the LHC are in line with standard industrial maintenance practice.

The data collected and the performance obtained provide useful information for the definition of the operation scenarios strategy of CERN's installations but also future large cryogenic systems.

An effective maintenance program can be successfully and efficiently implemented if solid bases in terms of analysis, methodology, documentation and procedure are implemented via a CAMMS. A work control system and the use of Key Performance Indicators are required to efficiently adapt and improve the maintenance program to the requirements and constraint of the operation.

Over the next few years CERN plans to further improve the quality, efficiency and cost of the maintenance and operation activities while freeing resources to support the design and construction activities for the increase in luminosity of the LHC and other new projects. This will be accomplished by improving the CAMMS capabilities and by the award of a new operation and maintenance industrial contract based on a mixed task oriented and performance obligation contract according to the strategy and operational maturity of the installations.

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