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Cryogenic operation methodology and cryogen management at CERN over the last 15 years

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CERN, the European Organization for Nuclear Research has progressively implemented and brought into operation an impressive number of cryogenic units (34). The paper will present the evolution of CERN's cryogenic infrastructure and summarize results from cryogenic operation cumulating 590'000 running hours over the last fifteen years. The implemented methodology allowing reaching a high level of plant reliability will be described. CERN also becomes an intensive user of cryogens. Contracts for the delivery of 320 t of liquid helium and 70'000 t of liquid nitrogen have been adjudicated. The paper will describe the procurement strategy, the storage infrastructure and cryogen inventory.

INTRODUCTION

The European Organization for Nuclear Research (CERN) is an international organization, seated in Geneva, Switzerland, with 20 Member States. CERN is providing scientific collaboration among European States in the field of high-energy physics research and to this end it designs, constructs and operates the necessary particle accelerators and the associated detectors.

In order to fulfill its scientific program, CERN has progressively implemented and brought into operation several helium cryogenic refrigeration plants, totalizing 34 units (33 for helium and one for nitrogen) including their ancillary equipment. Liquid helium plants are used for the cooling of superconducting magnets of accelerators, physics detectors and tests bench facilities. Liquid nitrogen is used for pre-cooling of the above mentioned equipments, for boosting the helium plant liquefaction capacity, for purification systems and for cooling of liquid argon and krypton calorimeters used by physics detectors.

For the operation and maintenance (O&M) of such a large spectrum of cryogenic refrigeration units, CERN has established, for strategic reasons since 1994, partnerships with specialized industrial service providers. In parallel, the procurement of the associated cryogens (high-grade helium and liquid nitrogen) is achieved by placing contracts with several major industrial suppliers in order to secure deliveries.

CRYOGENIC EQUIPMENT INVENTORY

CERN's cryogenic equipment was specifically procured or adapted from existing, according to the technical requirements of the four main user's communities: particle accelerators, physics detectors (on colliders or fixed targets), large test benches and laboratory-scale test facilities. The present total helium cryogenic refrigeration capacity at CERN represents a total of 164 kW at 4.5 K. With the implementation of the LHC accelerator cryogenic system, [1], consisting in eight helium refrigeration units providing a capacity of 18 kW at 4.5 K coupled to eight 2.4 kW at 1.8 K refrigeration units in order to achieve the final temperature operation requirements, [2], CERN has reached an unprecedented level of helium refrigeration capacity (see Table 1).

From the cryogenic O&M point of view, since 1990, the main users of cryogenics at CERN were the following:

The LEP (Large Electron Positron) collider included eight low-β superconducting magnets and 288 RF cavities (decommissioned in 2000 after 10 years of successful operation) and its associated physics detectors (ALEPH, DELPHI) using superconducting magnetic spectrometers, totalizing 125 t of cold mass and cooled at 4.5 K by several independent helium refrigeration units, [3], [4].

The SPS (Super Proton Synchrotron) included two twin modules of superconducting accelerating cavities, [5] and several fixed target physics detectors using a wide range of large spectrometer type superconducting magnets cooled at 4.5 K by dedicated independent helium refrigeration units continuously adapted according to CERN's approved scientific program requirements.

Several cryogenic test bench facilities for R&D programs as well as important series test benches for superconducting wires, cables and magnets for the LHC (Large Hadron Collider) project. All LHC superconducting magnets have been fully tested in their nominal cryogenic conditions before transfer and installation in their final underground position in the accelerator.

Finally, the LHC (Large Hadron Collider) presently under commissioning at CERN includes a string of 26.7 km of superconducting magnets cooled at 1.9 K (37'500 t of cold mass). The associated LHC physics detectors (ATLAS, CMS) includes their superconducting magnetic systems cooled at 4.5 K (respectively 1275 t and 225 t of cold mass) and cryogenic detectors (calorimeters) using liquefied gases (83'000 liters of ultra-pure liquid argon), [6].

Table 1 summarizes the number and present affectation of helium and nitrogen units with their installed capacity at CERN. Refrigeration power is generally provided at several levels of temperature but for conversion reasons equivalent capacity at 4.5 K is given, when applicable.

Table 1 Helium and nitrogen units & refrigeration capacity at CERN

Helium refrigeration capacity at 4.5 K [kW]	**Units**	**Affectation**	**Total helium refrigeration capacity at 4.5 K [kW]**
18	8	LHC collider	144
6	1	LHC detector (ATLAS)	6
6	1	SM18 LHC Series test benches	6
1.5	1	LHC detector (CMS)	1.5
1.2	1	WA test benches	1.2
0.8	2	Physics detectors	1.6
0.4	9	SPS Detectors, Tests benches	3.6
0.1	1	SPS Test bench	0.1
Total	**24**		**164**
Helium refrigeration capacity at 1.8 K [kW]			**Total helium refrigeration capacity at 1.8 K [kW]**
2.4	**8**	LHC collider	**19.2**
Helium refrigeration capacity at 40-80 K [kW]			**Total helium refrigeration capacity at 40-80 K [kW]**
20	**1**	LHC detector (ATLAS)	**20**
Nitrogen refrigeration capacity at 84 K [kW]			**Total nitrogen refrigeration capacity at 84 K [kW]**
20	**1**	LHC detector (ATLAS)	**20**
GRAND TOTAL	**34**		

OPERATION METHODOLOGY

Before 1994, CERN was directly responsible in organizing and performing all technical tasks related to the O&M of the Organization's cryogenic units and infrastructure. During 1994 and since then, CERN has taken the strategic decision to outsource the cryogenic O&M activities by establishing a partnership with specialized industrial services providers.

Two complementary main reasons have guided this important decision: the increasing R&D work load and human resource needs in view of the LHC project approval process and the wish, in parallel, to adopt and reach the state of the art of industrial standards for cryogenic O&M activities thus optimizing the plant's high reliability requirements, the associated human resources and the related operational and maintenance costs.

Following the Organization's selection criteria and purchasing rules, CERN has placed a first service contract covering the operational period from 1995 to 2000 with a consortium of industrial partners from the Air Products (UK) and Thomson (F) firms. This first partnership covered essentially the cryogenic operation requirements for the scientific program of LEP (accelerator, ALEPH & DELPHI detectors), SPS (accelerator and several fixed target detectors) and existing test facilities benches.

Major activities included in the first outsourcing contract were: under continuous production ensure, the control and monitoring of the cryogenic processes, the minor maintenance and emergency repairs following approved procedures, the major maintenance activities in line with accelerator shutdowns agreed in advance with CERN, the update of all technical documentation, the management of the spare part stock, the management of expendables and general or specialized tools. Maintenance costs have been defined as lump sums per plant and spare part procurement was under CERN's responsibility.

In order to ensure smooth transition of operational responsibility from CERN to the industrial partner, it was decided to implement a "two phase" approach. The "preparatory phase" lasted three years (1995-1998) and allowed to the industrial partner to get familiar with the plants, play an active role in operating them under CERN's close supervision, develop and obtain approval from CERN for its own systematic methods by establishing operational and maintenance procedures and tools and thus progressively taking in charge the maintenance tasks and emergency repairs of the entire park of cryogenic plants and ancillary infrastructure.

At the end of this "preparatory phase", the competence and reliability of the industrial consortium has been positively evaluated. CERN then launched the second "Operational phase" (1998-2000) by transferring the O&M responsibility to the industrial partner in a "full delegation task" oriented contractual process. On average, 40 employees from the consortium covered the O&M requirements during the 2nd phase with peak values of additional technical support teams (from firm's rear base) during accelerator shutdown. CERN's responsibility was concentrated on the coordination with the users, the supply of the cryogenic fluids, the process control systems and all external utilities (electrical power, cooling water, compressed air and computing networks).

Based on its own operation experience before 1994, CERN implemented contractual performance evaluation indicators specifically dedicated to the function of each cryogenic installation. Plants have been divided in two categories on whether used for physics installations (accelerators and detectors) running in a regular basis on steady state for well defined operational periods, or for testing components under R&D programs and centralized cryogenic services and supplies. The annual result of the global performance evaluation led to the attribution of a bonus or penalty to the industrial partner proportional to the contract's yearly value. Table 2 summarizes the non availability rates for breakdowns of cryogenic and non cryogenic origin as well the total mean rate of non availability of the cryogenic plants with respect to the cumulated running hours.

During the year 2000, with the decommissioning of the LEP accelerator and its detectors, CERN came, from the cryogenic operation point of view, in a new user's era dominated by the intense O&M activities related to the R&D and cryogenic test benches in view of the LHC implementation project. The outsourcing strategy for the cryogenic operation activities was again validated and a new invitation to tender was launched for covering the transition period from the LEP to the LHC (accelerator and detectors) commissioning and start-up. However, in addition to R&D, test benches and commissioning activities, CERN's scientific program requested the continuation of the operation for several cryogenic units coupled to superconducting spectrometer magnets essentially based on fixed targets receiving beams from the SPS accelerator. In parallel, all centralized cryogenic services and laboratory scale activities continued without interruption.

The challenge of the new industrial partnership was to be able to efficiently cover such a wide variety of cryogenic O&M activities, most of which were not linked to a regular basis functioning program but related to the works of a very large R&D, test benches, installation and commissioning program of the new LHC cryogenic installations. The corresponding planning was permanently adapted to the constraints of production, tests, installation and commissioning activities of the LHC project.

CERN has placed the new contract for an industrial partnership with a consortium constituted from Air Liquide (FR), Linde (CH) and Serco (DE) for covering an initial period from 2001 to 2005 with the possibility of several contractual options of yearly extensions. The present partnership is extended up to mid of 2009. Presently, nearly 63 employees from the consortium are working in situ for the O&M of CERN's cryogenic infrastructure covering activities for operation (42), technical support and maintenance (17), management and secretariat (4).

From the technical point of view, the main changes from the former outsourcing contract were the following: the introduction of work packages regrouping plants and infrastructure by nature of activities, the implementation of shift work (24h/24, 7d/7) for covering the very intense cryogenic series tests of the LHC magnets during several years, the strong optimization of the maintenance costs by introducing unit prices per equipment linked to the cumulated running hours instead of lump sums and finally, the procurement of spare parts was passed under the responsibility of the industrial partner. For increased contractual flexibility during the transition period, the O&M program and related contract amount is discussed and approved on yearly basis in order to optimize costs with respect to the project's planning updating.

For cryogenic O&M activities linked to physics programs and central cryogenic services, based on the strong experience gained during the first task delegation contract, new performance indicators have been again introduced for contractual evaluation (allowing bonus or penalty). For the breakdown times not generated by a cryogenic origin, typical profiles of recovery time versus production stops duration have been implemented. Table 2 summarizes the number of the cumulated running hours for the 2001-2007 period and the non availability rates for breakdown times of cryogenic and non cryogenic origin. Two important conclusions have to be highlighted. Firstly, for breakdown of cryogenic origin, strong operation experience has been gained over the last years thus permitting to decrease the non availability rate from 2.2‰ to 0.60‰. Secondly, due to the nature of the cryogenic operation during 2001-2007, dominated by the tests facilities, their infrastructure and the commissioning runs, the noticeable increase of the non availability rate due to a non cryogenic contractual origin such as failure of external utilities or pollution of helium circuits by the users.

Table 2 Cryogenic plants availability results over the 1992-2007 periods

Operational periods	**1992-2000**	**2001-2007**	**1992-2007 Overall**
Total number of cumulated running hours	320'000	270'000	**590'000**
Breakdown time of contractually cryogenic origin (Mean rate of non availability with respect to the running hours)	2.2 ‰	0.60 ‰	**1.47 ‰**
Breakdown time of non cryogenic origin (Mean rate of non availability with respect to the running hours)	2.9 ‰	7.14 ‰	**4.84 ‰**
Total mean rate of non availability	**5.1 ‰**	**7. 74 ‰**	**6.31 ‰**

The main causes of breakdown of cryogenic origin were the following: helium circuit pollution (leaks or faulty operation) essentially by air and/or humidity, instrumentation failures (interlocks, power supplies, control valves blockages), helium compressor system failure (due to incorrect maintenance, leaks located on heat exchangers, abnormal vibration level), process control software crashes, rare case of oil pollution in helium circuits. The main breakdowns of non cryogenic origin were the following: loss of external utilities (electrical power, cooling water, compressed air, computing network) required for the plant and user's operation, helium circuit pollution by impurities having their origin in user's primary circuits, faults in detection of resistive transition of the superconducting devices using cryogenics, real resistive transitions of superconducting devices (i.e. induced by beam losses)

CRYOGEN MANAGEMENT

With the completion of installation of the LHC cryogenic system, the evolution of CERN's cryogenic storage infrastructure for cryogen (helium and nitrogen) has been drastically upgraded. Table 3 summarizes the gas and liquid helium storage capacity at CERN and the LHC. Table 4 summarizes the liquid nitrogen storage capacity at CERN and the LHC.

Table 3 Gas and liquid helium storage capacity at CERN (in brackets capacity dedicated to the LHC)

Gas tank capacity [m^3]	**250 (at 2.1 MPa)**	**80 (at 1.5 & 2.1 MPa)**
Number of units at CERN	58 (58)	65 (40)

Liquid tank capacity [liter]	**120'000 (fixed)**	**25'000 (fixed)**	**11'000 (mobile)**	**6'000 (fixed)**
Number of units	2 (2)	1	2	1

Table 4 Liquid nitrogen storage capacity at CERN (in brackets capacity dedicated to the LHC)

Container capacity [liter]	**50'000**	**40'000**	**27'000**	**20'000**	**15'000**	**10'000**	**6'000**
Number of units	14 (13)	2	1	2	2	1	7

Following an accidental or scheduled plant shutdown, the LHC helium cryogenics for both accelerator and detectors privileges the helium recovery to the 250 m^3 (2.1 MPa) gas tanks thus avoiding capital investment and maintenance of expensive recovery and high pressure purification systems. For high-grade helium gas transfers, a new ring line, 2 MPa, 27 km long dedicated to LHC operation was successfully commissioned completing the already CERN existing infrastructure for helium recovery and transfers (high grade, 20 MPa, 5 km long and low grade, 3 kPa & 20 MPa, 3 km long each).

Procurement of high-grade liquid helium and liquid nitrogen

Following the Organization's selection criteria, purchasing rules and International Standards for the management of helium and nitrogen facilities including production, trading, transport and delivery, CERN places renewable supply contracts with several qualified industrial partners in order to secure deliveries.

Liquid helium is delivered in 11'000 US gallon transportable containers directly to CERN's technical sites and stored in liquid phase in the fixed or transportable containers or injected to the low pressure of the cryogenic plant compressor system. Normal minimum delay for delivery of one full container is one working week with an option for short notice delay (48 h) in case of major accidental loss. The full LHC (accelerator & detectors) helium inventory represents 136 t (respectively 130 t and 6 t of helium). The LHC accelerator storage capacity in situ is 75 t and the option of "virtual storage" for 55 t (at supplier's premises) was implemented in the contracts with the industrial partners. The full LHC helium inventory was successfully completed at CERN beginning of July 2008. The present total helium inventory at CERN is 140 t (in gas or liquid phases).

Liquid nitrogen in transportable containers (20 t as minimum quantity at one time) is delivered to CERN's technical sites and stored outdoors in several vertical containers. Normal minimum delay for delivery is 24 hours. Specific administrative conditions have been implemented for the LHC cooling down deliveries on a 24h/24, 7d/7 basis. Quantities from 2'500 t in 11 continuous days up to 10'000 t in 33 continuous days (with one month preliminary notice) are requested. The first full LHC nitrogen pre-cooling was successfully completed during June 2008 (totalizing 10'000 t).

Table 5 summarizes the helium and nitrogen deliveries at CERN for the 1998-2007 periods, the 2008 present status as well as global projection for the 2008-2011 periods. In order to highlight the intensive use of cryogen at CERN, it is noticeable that estimated quantities of cryogens (for both helium and nitrogen) to be delivered over the 2008-2011 years are nearly equivalent to CERN's effective use over the last 10 years (1998-2007).

Table 5 Helium and nitrogen deliveries at CERN (1998-2007) and estimated quantities for 2008-2011

Year	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**Total**	**2008 (06/08)**	**2008-2011 estimated**
Helium [kg]	21980	26874	29682	21598	21613	35675	28224	40290	61166	77760	**364862**	109000	**320000**
Nitrogen [t]	3982	3046	5388	4183	4344	5147	7912	9858	9061	11518	**64439**	11532	**70000**

OUTLOOK

Operation of cryogenics for the LHC accelerator and physics detectors will require a very high availability rate and technical reliability. Over the last fifteen years of cryogenic O&M activities in several operational modes, solid experience with excellent availability results, resources and cost optimization, was acquired at CERN. Such operational experience will undoubtedly help in the near future for organizing the new structure and implementing the conditions required for a successful and extremely highly reliable LHC cryogenic operation.

Concerning the cryogen management, with such large helium inventory, operational and maintenance activities shall ensure and maintain the safe storage (in the accelerator components, gas or liquid buffers) and manage, if required, the “virtual storage” option. Specifically for the liquid nitrogen deliveries, logistics for full LHC cooling requirements (10’000 t in 33 continuous days) have to be secured. To that scope, CERN implemented several new supply contracts for an estimated quantity up to 320 t of liquid helium and 70’000 t of liquid nitrogen for covering the 2008-2011 years.

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