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First Assessment of Reliability Data for the LHC Accelerator and Detector Cryogenic System Components

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Abstract

The Large Hadron Collider (LHC) cryogenic system comprises eight independent refrigeration and distribution systems that supply the eight 3.3 km long accelerator sectors with cryogenic refrigeration power as well as four refrigeration systems for the needs of the detectors ATLAS and CMS. In order to ensure the highest possible reliability of the installations, it is important to apply a reliability centred approach for the maintenance.

Even though large scale cryogenic refrigeration exists since the mid 20th century, very little third party reliability data is available today. CERN has started to collect data with its computer aided maintenance management system (CAMMS) in 2009, when the accelerator has gone into normal operation. This paper presents the reliability observations from the operation and the maintenance side, as well as statistical data collected by the means of the CAMMS system.

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ABSTRACT

The Large Hadron Collider (LHC) cryogenic system comprises eight independent refrigeration and distribution systems that supply the eight 3.3 km long accelerator sectors with cryogenic refrigeration power as well as four refrigeration systems for the needs of the detectors ATLAS and CMS. In order to ensure the highest possible reliability of the installations, it is important to apply a reliability centred approach for the maintenance.

Even though large scale cryogenic refrigeration exists since the mid 20th century, very little third party reliability data is available today. CERN has started to collect data with its computer aided maintenance management system (CAMMS) in 2009, when the accelerator has gone into normal operation. This paper presents the reliability observations from the operation and the maintenance side, as well as statistical data collected by the means of the CAMMS system.

KEYWORDS: CERN, LHC, cryogenics, operation, maintenance, reliability, availability, CAMMS, failure rates, MTBF, MTTF, RCM, TPM, key performance indicators

INTRODUCTION

The Large Hadron Collider (LHC) cryogenic system comprises eight independent refrigeration and distribution systems that supply the eight 3.3 km long accelerator sectors with cryogenic refrigeration power, as well as four refrigeration systems for the cryogenic refrigeration needs of the detectors ATLAS and CMS. The total refrigeration power is more than 160 kW at 4 K. The availability of the cryogenic installations is highly critical as the failure of most of the sub-systems will lead to an immediate stop of the accelerator beams or of the detector's data taking. CERN's cryogenic installations are built-up of several ten thousand components and the availability of the whole system will depend on the availability of certain large components as compressors, as well as the availability of small and tiny components as e.g. temperature sensors or electric connectors. The struggle for the best possible availability is a process that has not only accompanied the design, manufacturing or commissioning, but that will continue throughout the life-cycle of the installations. The ongoing task is to have at any time a good knowledge of the system's critical components and to identify bad actors that have had an impact on availability in the past. This means also that all systems, equipment or components have to be constantly reviewed to keep criticality information up to date and that the search and implementation of improvements for bad actor must be well implemented alongside the plant operation and maintenance. In other words, a complex and highly critical system as CERN's cryogenic refrigeration installations must be permanently accompanied by a reliability centred approach.

Now, about two years after the start of physics operation, some types of equipment that exist in large numbers on CERN's cryogenic installations have accumulated observation periods of up to several million operation hours which allows to draw first conclusions for the reliabilities of these components.

After explaining the reliability approach, firstly the operation contributions to availability and secondly the data collected by maintenance shall be explained.

INTRODUCTION TO THE RELIABILITY APPROACH

One of the first steps in applying Reliability Centred Maintenance (RCM) principles is establishing a Failure Mode and Effects Criticality Analysis (FMECA) which collects data on components and combines factors as failure modes, failure effects, failure severity, failure probability etc. and computes criticality values. One important input for the FMECA is in fact the failure probability or mean time between failures (MTBF). If no MTBF values are available from databases or suppliers, failure probabilities must be estimated on the basis of experience. However, this is extremely difficult as e.g. failure probabilities of high population components are easily overestimated and experts tend often to overestimate the criticality of their own systems. This results in a demand for reliability data on cryogenic components that can not be answered easily.

Third Party Reliability Data Sources

Reliability data is an important design asset in a number of industries e.g. in the military, aeronautics, nuclear or petrochemical sectors. For the specific requirements of these users, a number of specialized reliability databases listing MTBF data are available. Examples are the US Military Handbook 217 [1] which contains data on electronic components and the OREDA Offshore Reliability Data [2] which compiles data on

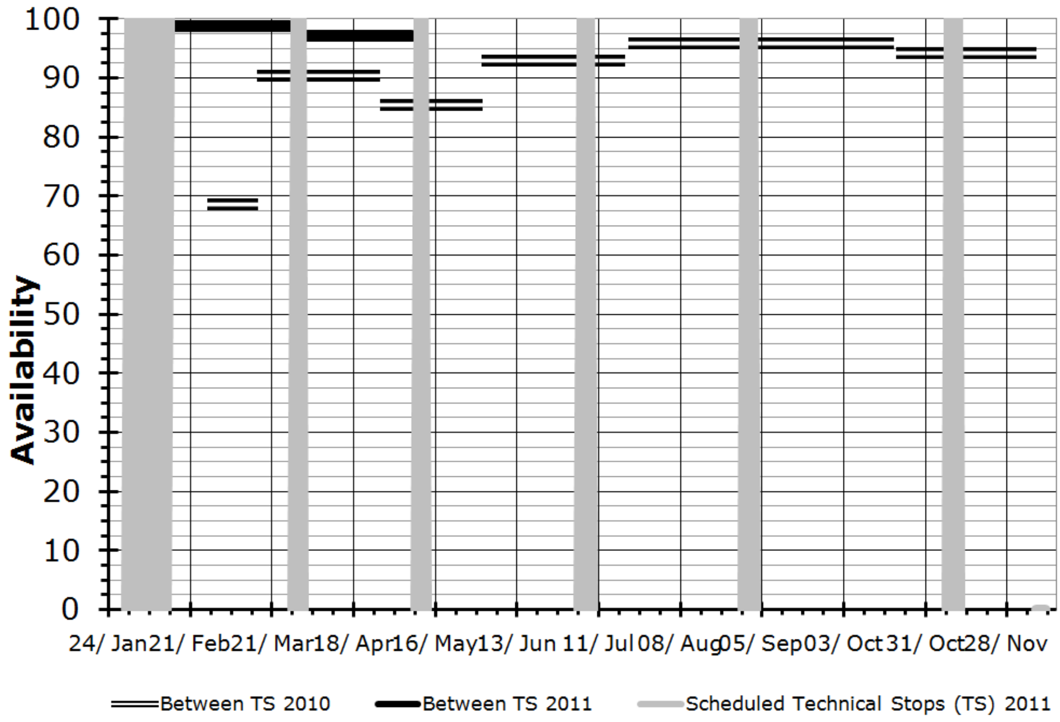

FIGURE 1. Availability of the LHC refrigeration system 2010 and 2011.

equipment for offshore usage and in particular safety equipment. Even though cryogenic installations are process plants and have therefore similarities with petrochemical installations, the operation conditions or in reliability terms the "required functions" and the environment conditions are quite different. Existing data must therefore be used with utmost care. Many components used in cryogenic installations are used in other industries too, but the fact that they have been adapted in one way or another to fit them to the particular needs of the cryogenic process may have an influence on their reliability.

The data collections that meet most closely the needs for reliability data on components used in cryogenic installations are the databases collected by Cadwallader and Pinna for the fusion engineering community [3-6].

Reliability Data Collection on Cryogenic Installations

Large scale cryogenic refrigeration exists already since the mid 20th century, but it remains a technology that is primarily used in the research environment, in particular for accelerators and fusion machines. The cryogenics community around the world is relatively small and due to its public research background rather open for information exchange. This means that important reliability issues become rapidly common knowledge amongst users as well as suppliers. In the past there have been only a few initiatives to collect systematic reliability data for cryogenic installations, and the number of reliability reports from individual installations is limited [7-15]. This might be explained by the fact that most laboratories will only dispose of one or very few cryogenic installations and do therefore not have sufficient hindsight. Even with more than one installation, reliable data collection is difficult due to the typically small fault populations or, in other words, due to the prevailing high availability values of many cryogenic components. In the research environment the link between reliability and cost, that can be established in industry, does not exist and is a missing motivator.

TABLE 1. Preventive, predictive and corrective maintenance over a 12 month period (5/2010 – 4/2011).

	Trade	Preventive maintenance (during yearly shut-down)	Predictive and corrective maintenance
Total number of work orders		1102	768
Break down of work order numbers by trade	Mechanics	380	325
	Instrumentation	487	354
	Vacuum	235	89
Total number of hours		2303	4564
Break down of hours by trade	Mechanics	1001	2567
	Instrumentation	714	1243
	Vacuum	588	754

CERN, with its huge cryogenic installation park, has the unique chance to collect meaningful reliability data which will be of great interest for both CERN's maintenance approach and the cryogenic community. However, collecting meaningful data requires a flawlessly functioning reliability approach.

CERN's Reliability Data Collection Method and Tool

One of the prerequisites for collecting meaningful data is a very high level of self discipline by all parties that are involved in the reliability observation, as each intervention must be recorded and painstakingly classified. The reliability approach furthermore requires that the intervention data is collected in a standardized way across system borders in order to allow their comparison. Ideally the data should be available in a common database as this is the only way to investigate interdependencies.

At CERN reliability has played an important role in the design and construction of the installations and numerous improvements and consolidations have therefore already been launched during the commissioning phase of the installations. However, long term data taking has in many cases only started together with the first beams and some further standardization of the data taking methods is still required.

For the cryogenic installations data taking is enforced, with a few exceptions, by a strict workflow implemented into the Computer Aided Maintenance Management System (CAMMS) Infor EAM for both corrective and preventive maintenance interventions. In the CAMMS each intervention work order is attached to the concerned functional position.

All the functional positions are organized in a tree structure and classified in classes and categories to simplify the data analysis. Furthermore, records of all the spare parts that have been used during maintenance interventions are attached to the concerned work order. However, it should be noted that not all above conditions have been available at the same date. The implementation of the CAMMS for the cryogenic installations was launched at about the same time as the start of the accelerator in 2009.

TABLE 2. Work order statistics by equipment type over a 12 month period (5/2010 – 4/2011).

	Preventive maintenance (top 3)		Predictive and corrective maintenance (top 3)	
Trade	**Equipment category**	**Number of work orders**	**Equipment category**	**Number of work orders**
Mechanics	Screw compressors	101	Compressor station	110
	Compressor station	97	Screw compressor	38
	Recovery compressor	26	Oil pumps (screw type)	24
Instrumentation	Compressor station	104	Compressor station	63
	Refrigeration system	101	Control valves	34
	Electrical cubicles	80	Cold box	30
Vacuum	Cold box	71	Cryogenic installation	12
	Rotary vane pumps	57	Diffusion pump	12
	Diffusion pumps	36	Pressure transmitter	9

MAJOR OPERATION CONTRIBUTIONS TOWARDS AVAILABILITY FOR LHC

After successful cool-down and tuning of LHC, operation had to face a series of problems limiting the availability of the cryogenic system, from instrumentation to major cryoplant stops. Very quickly, periodic meetings involving operation, technical support such as electricity, instrumentation, controls, mechanics and maintenance were set-up. One of the main aims was to evaluate, if encountered problems were isolated cases or would reveal systematic issues, for which mitigation programs and consolidation programs had to be foreseen [10,11] like for the instrumentation fuses or the current leads cooling valves.

During the 2010 operation period and besides ongoing consolidation programs, three major types of stops requiring specific treatment have been identified:

Recovery time of the order of 24 hours: This concerned eight stops of the 4.5 K refrigerators. An external cause was the intolerance to electrical glitches of the high voltage power supply, which was resolved by delaying the alarms to over 120 ms and which has proven to cope with all experienced glitches since (about 25 LHC beam stops have been due to non-cryogenic systems in the same period). Consolidation of some 24 VDC power supplies for instrumentation is also under evaluation.

Recovery time of the order of 12 hours: This concerned seventeen stops of the 1.8 K units with cold compressors. Seven of them were due to ageing electronics for active magnetic bearings or frequency drives which were all consolidated during the Christmas break with a dedicated preventive maintenance program that is now implemented for similar equipment. Four stops were required to warm-up the inlet filter of cold-compressors that are operating at sub-atmospheric pressure. Several small leaks on welded joints have in the meanwhile been identified as the cause for the leaks from atmosphere. The remaining six cases concern operation learning curves or single hardware failures.

Recovery time between minutes to a few hours: The mitigation and consolidation program in place allowed to reduce the number of stops due to the cryogenic system from about three cases per week in spring 2010 to about one case per week at present, which confirms that the improvements have been effective.

Since the beginning of 2011, the failure modes are dominated by PLC's faults, most of them being induced by single event upsets due to energetic neutrons emanating from the LHC machine, which has already reached rather high intensities. A large majority of the

TABLE 3. Work order statistics by maintenance tasks over a 12 month period (5/2010 – 4/2011).

Top 10 maintenance tasks	Numbers
Digital inputs – switches – inspection and adjustment	1,526
Heaters – heaters elements – inspection:	233
Safety valves – standard revision	192
Valves – inspection of functioning of automatic valves	191
Vibration measurement – motor-compressor set	190
Motors – inspection	161
Instrumentation – debugging of instrumentation	140
Control cubicles – replace (without debugging) any extra low voltage component	128
Couplings – adjustment of flexible couplings, verification, correction of alignment	91
Power supplies – lockout tagout (includes locking and tagging and unlocking)	90

concerned PLCs is already earmarked for a relocation program with which they shall be moved from the exposed areas to sheltered zones and avoid the perturbation of operation in the long term.

The continuous improvement of the availability throughout the operation periods 2010 and 2011 is displayed in FIGURE 1. The methodology in place to identify the bad actors that are influencing the cryogenic refrigeration system's availability shall be continued and will hopefully help to tackle problems during the period when there is still some margin in the cooling capacity, i.e. before LHC is operated at its nominal energy and luminosity.

FIRST RELIABILITY DATA FROM MAINTENANCE

Besides operation itself, maintenance can have an important impact on reliability and availability. The compilation of data presented in the following paragraphs has been collected on the cryogenic refrigeration systems in the period 2009-2011 via the maintenance process. It must be noted that the statistics do not include data on the tunnel instrumentation and the controls components as their maintenance is managed with different tools.

Preventive Maintenance and Corrective Maintenance

One factor that indicates the evolution of the maintenance process from reactive, i.e. "go and fix it", to planned, i.e. "fix it before it fails" is the ratio between preventive, predictive and corrective maintenance. TABLE 1 lists the statistics for a 12 month period. The preventive maintenance had to be carried out entirely in a two week slot during the Christmas break. Most of the predictive and corrective maintenance has been carried out during one of the technical stops (TS).

Another interesting detail is the question which type of equipment receives how much maintenance attention. TABLE 2 break down the maintenance interventions by equipment type and last but not least TABLE 3 lists the top 10 maintenance tasks during the reference period.

TABLE 4. MTBF estimation for a few selected components (observation period 27 months).

Description	Subject to PM	Number of spare parts used	Observed compo-nent populat.	system operation time	estimated MTBF
Mechanical components					
Valve cone seals cryogenic valves		41	~1'100	~18'000h	~0.5 Mh
Valve sealing issue warm valves		182	~13'000	~18'000h	~1.3 Mh
Safety valves and parts thereof	X	95	~3'100	~18'000h	~0.6 Mh
Compressor shaft seal – all compressors	X	11	83	<18'000h	~0.12 Mh
Compressor shaft seal – worst type	X	8	20	~18'000h	~0.045Mh
Oil pump shaft seal – worst type	X	13	12	~12'000h	~0.011Mh
Instrumentation components					
Pressure transmitters – all types		30	~3'100	~19'700h	~2 Mh
End switches		31	~4'000	~19'700h	~2.5 Mh
Electro-valve		77	~1'500	~19'700h	~0.38 Mh
Electro-pneumatic positioner	X	12	~1'400	~19'700h	2.3 Mh

Identifying Bad Actors

The operation approach to identifying and tackling bad actors has been described above. Another way of identifying bad actors is the analysis of the corrective maintenance interventions for recurring spare part usage and accumulation of work orders on individual components. TABLE 4 contains a selection of a few numbers of spare part consumptions and the calculation of the mean time between failures (MTBF) of the associated equipment.

For many component types, none or very few spare parts have been consumed and the MTBF values are probably much higher than the values presented here. However, a more detailed break-down shall be performed in the future.

There are a few failures that are worth mentioning individually from the maintenance side due to their impact or due to their frequency: the break-down of one screw compressors and the near-break-down of a second screw compressor due to the failure of axial bearings; a leakage in a large plate fin heat exchanger; recurring problems with one type of compressor shaft-seals as well as one type of oil pump shaft seals; erroneous moisture measurements of the oil analysis laboratory that have led to unnecessary leak searches; and the possibly unnecessary installation of a drier. However, due to redundancies and the workarounds that are possible with the reduced power of the accelerator, none of the above problems has had a significant impact on the availability of the cryogenic refrigeration systems.

CONCLUSIONS

CERN has applied a reliability approach throughout all the project stages from design, manufacturing, commissioning and first cool-down to operation and maintenance. Both operation and maintenance have developed complementary strategies to identify bad actors and to improve the reliability of the installations. The operation experience shows that the critical failures can be grouped into distinct families of small, medium and high impact. The CAMMS used for the maintenance process allows today to identify hidden recurrent problems and helps to concentrate the future efforts on critical components. The methodology in place shall be continued and will hopefully help to tackle problems during the period when there is still some margin in the cooling capacity, i.e. before LHC is operated at its nominal energy and luminosity.

The collected reliability data confirms the generally assumed high reliability of many cryogenic components, but a detailed analysis is still to be performed. The high availability of CERN's refrigeration systems of more than 95% that has been reached rapidly in the operation period since 2010 is today fully compatible with the LHC physics program.

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