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ITER Cryoplant Final Design and Construction

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Abstract. The ITER Tokamak supraconducting magnets, thermal shields and cryopumps will require tremendous amount of cooling power. With an average need of 75 kW at 4.5 K and of 600 kW at 80 K, ITER requires a world class cryogenic complex.

ITER then relies on a Cryoplant which consists in a cluster of systems dedicated to the management of all fluids required for the Tokamak operation. From storage and purification to liquefaction and refrigeration, the Cryoplant will supply to the distribution system, all fluids to be circulated in the Tokamak. It includes Liquid Helium Plants and Liquid Nitrogen Plants, which generate all of the refrigeration power, an 80 K helium loop capable to circulate large quantities of helium through thermal shields, and all the auxiliaries required for gas storage, purification, and onsite nitrogen production.

From the conceptual phase, the design of the Cryoplant has evolved and is now nearing completion. This proceeding will present the final design of the Cryoplant and the organization for the construction phase. Also the latest status of the ITER Cryogenic System will be introduced.

1. Introduction

The purpose of the ITER Cryogenic system is to provide the required operational conditions for the magnet system, vacuum system and small users like diagnostics. The magnet system consists of superconducting magnets coils, structure and current leads, and is supported by 80 K thermal shields system. The vacuum system consists of cryo-pumps for torus and cryostat, cryo-pumps for Neutral Beam Injection (NBI) and Pellet Injection System (PIS). The users of the Cryogenic system require helium cryogen at temperature levels of 4.5 K, 50 K and 80 K and nitrogen at either 80 K or ambient temperature. The Cryogenic system needs to satisfy all operational modes of the users at various stages of plasma operation. To satisfy the operational modes and resulting requirements, the ITER Cryogenic system has been divided according to the ITER Geographical Breakdown System (GBS) in two different locations namely the Cryoplant system (in Cryoplant buildings and Cryo-bridge) and the Cryodistribution system (in the Tokamak).

This proceeding will focus on Cryoplant providing an overview and argues about design evolutions since the conceptual design phase of the Cryoplant, and the Cryoplant organisation for the construction phase.

2. ITER Cryoplant final design

The Cryoplant, which namely includes the LN_2 Plants, the 80 K Helium Loops and the LHe Plants, the storages and the recovery and purification system (refer to the diagram in figure 1) will consist in one of the largest clusters of cryogenic equipment in the world. The Cryoplant has now completed its final design with some evolution through all design phase. The following descriptions and comparisons are based on ITER conceptual design referenced in [2] and [3].

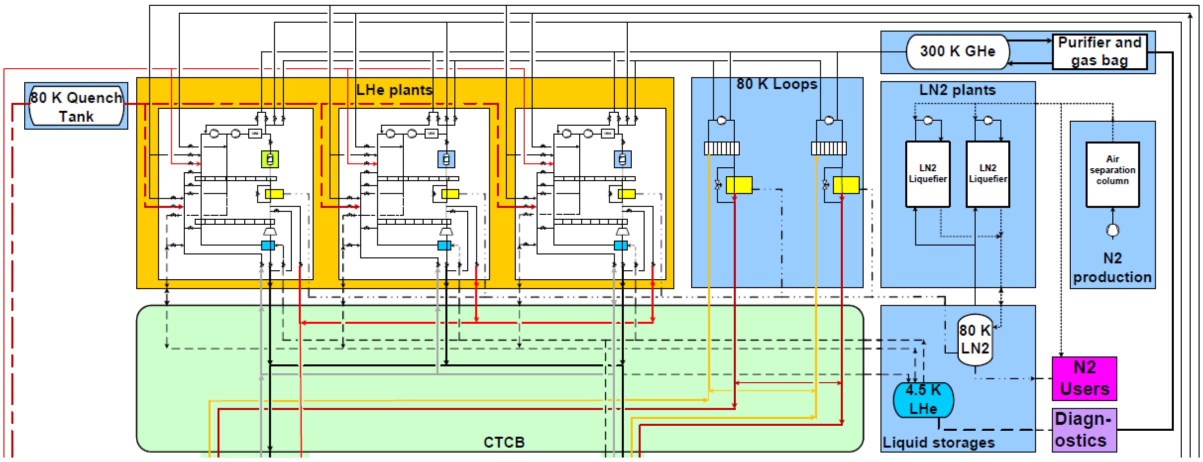

Figure 1. Simplified diagram of the ITER Cryoplant.

The following Cryoplant sub-systems or transverse design activities has involved and are described here under.

2.1. *The Storages*

The main function of ITER storages is to store the helium and nitrogen inventory of the Cryogenics system, including magnets, cryopumps and thermal shield as well as the necessary volume to control the system in all operating scenario.

The storage design is among ITER Cryoplant the most visible changed following the conceptual phase as shown in the comparison figure 2 and 3 below. The final design choice is closed to the alternative solution specified by ITER at the conceptual phase to the European Domestic Agency in charge of this procurement. The final design is focusing on liquid form rather than gas form. This choice lowers the Capital Expenditure (CAPEX) and save space without degrading the plant control and operation.

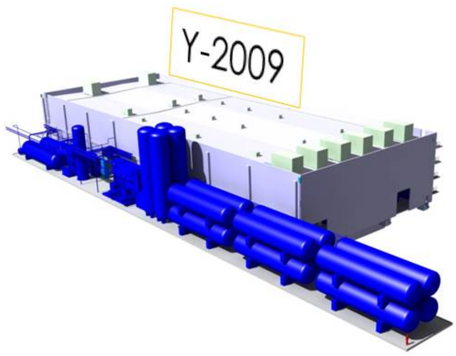

Figure 2. ITER storage configuration in Cryoplant Area 53 at Conceptual Design.

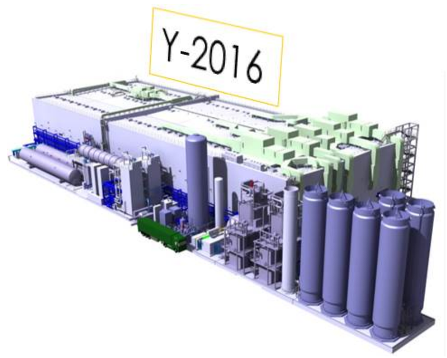

Figure 3. ITER storage configuration of Cryoplant Area 53 at Final Design. .

The table 1 below compare the conceptual and the final arrangement of the helium storages consisting of Gas Helium (GHe) tanks, cold Quench Tanks (QT) and Liquid Helium (LHe) tank.

Table 1. Storages configuration from Concept to Final Design.

Type of tank	*Conceptual Design* Number x Volume [m^3]	*Final Design* Number – Volume [m^3]
GHe pure	16 x 330 m^3	5 x 400 m^3
GHe impure	0	1 x 400 m^3
LHe	1 x 50 m^3	1 x 190 m^3
QT	2 x 360 m^3	2 x 360 m^3
GN_2	1 x 100 m^3	1 x 125 m^3
LN_2	2 x 100 m^3	1 x 300 m^3

Impure helium storage was added to act as dumper for the purification system and to minimize the treatment capacity of the helium purifier downstream the recovery compressors. The impure storage has the same design as others GHe tanks and can be used to manage the pure inventory.

Even if the Quench tanks have not changed, in volume its designed has been modified. The cooldown is done by the 80 K Helium Loops, the heat leaks are compensated by an external helium loop cooled by liquid nitrogen.

The nitrogen tanks capacity has increased to cope with the design of the LN_2 Plants when used in boosting mode in order to reach the maximum operating scenario, as well as to minimize the nitrogen delivery on site.

2.2. The Plants

Each plant, constituting the Cryoplant, is remained closed to the conceptual design in overall aspect. The process and process control as described for the ITER LHe Plants in [5] have evolved and some piping interfaces were adjusted with regards to the detail design of sub systems. The Cryogenic system will require large operating cost and is critical for the Tokamak operation. Energy saving, operation loss, availability and reliability were a design priority.

ITER Cryogenic and Buildings team’s first priority were to limit the risk that would have been related to the use of gas-powered heating system on a nuclear site. The final design choice includes a Heat Recovery System of 12 MW, described in [4], which will provide heat to all ITER buildings. This choice is not only an efficient and remarkable energy saving, but as often when looking at overall design taking into account the global warming and climate change a way to reduce CAPEX and Operational Expenditure (OPEX).

Part of the efficient collaboration in between Cryogenic and Building teams is the mutualisation of nitrogen production and distribution. Indeed Cryogenic system will use a large amount of nitrogen either in closed refrigeration loop or open loop (for purging or cooling) and Building is in charge to procure and distribute nitrogen among all ITER users. The final design adds a GAs Nitrogen (GAN) generator. The required capacity is about 50 tons / day. This plant will enable ITER to get rid of delivery hazards, to compensate the nitrogen waste, as well as to design the main liquid nitrogen plants on an average capacity (reducing the CAPEX of nitrogen refrigerator) rather than a peak cryogenic load at 80 K during the Tokamak cooldown scenario.

The last system added since the conceptual design is dependent of the compressor design choice and technology chosen for the 80 K Helium Loops. The warm centrifugal compressor will have significant helium leaks on the dry shaft seal. For limiting the helium loss during operation, a helium recovery and leak treatment system is integrated.

2.3. The Test Tools

The test tools to measure the performance of each system were identified and required at end of conceptual design to properly test the required functionalities and capacities of each plant.

The LHe Plants are delivered with a test cryostat (refer to figure 4 and 5), permanently attached to one of the Cold Box (CB3) with which it will share a common vacuum and headers. The test cryostat process piping will be connected to the Cryoplant Termination Cold Box (CTCB) and will allow testing each CB individually or interconnected. The main advantage of this design choice is to minimize the mechanical work after each cold box test as well as to use this test cryostat at any time after maintenance. It could be also used during ITER Tokamak operation to supply the LHe used to boost the plants. The heaters immersed in the test cryostat LHe phase separator is sized for an isothermal load of 75 kW at 4.5 K. The total installed electrical power inside the test cryostat is 215 kW.

Existing atmospheric heaters are used to simulate the non-isothermal load with a return temperature of 300 K.

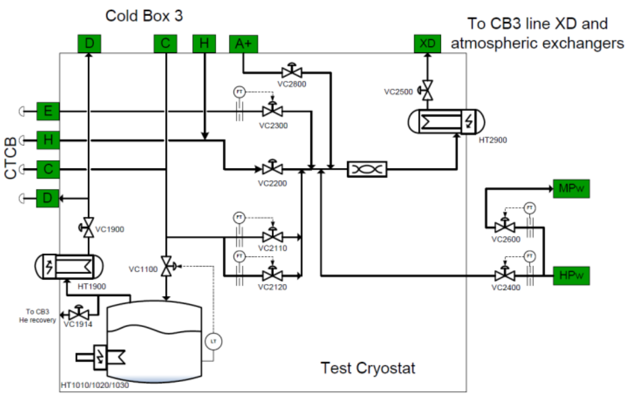

Figure 4. L He Plant test cryostat PFD.

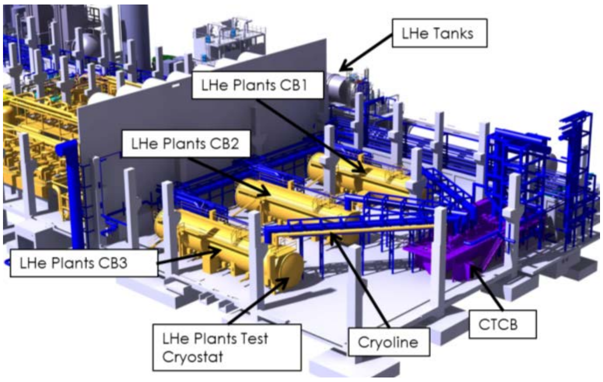

Figure 5. LHe Plants test cryostat integration

Similarly, the LN_2 Plants and the 80 K Helium Loops are going to be tested with a heater cold box designed to treat non-isothermal load from 80 K to 300 K.

2.4. Mechanical Design

ITER Cryoplant components are designed to withstand loads during normal, accidental and exceptional conditions. Five types of loads were applied and classified as per the Table 2.

Table 2. Type of loads and their origin.

Inertial	Pressure [P]	Thermal [T]	Assembly	Fatigue
Gravity acceleration	Dynamic fluid [P]	Fluid [T] In Operation	Loads – handling operations	load cycles
Transport accelerations	Static fluid [P] (tests)	Fluid [T] Cold test		
Seismic actions	Loss of Insulation Vacuum I (LIV-I) – Air ingress			
Equipment vibrations	LIV-II – Internal rupture			
Flow-induced vibrations	Purge operation			

In addition to loads due to normal operation and occasional conditions indicated in the table 2 above, the components are designed to withstand accidental hazard due to earthquake.

For the Cryoplant components, except the storages, are considered Non-nuclear Seismic Class (NSC) and the applicable code for seismic design is the Eurocode EN-1998. During the design, two states are checked:

- The investment protection state;
- The no collapse state related to the French law for normal and industrial buildings.

For the storages which are seismic-classified structures, the design has been done under a design-basis earthquake (named SL-2) corresponding to a distant earthquake with an upper-bound spectrum for the conservative safety earthquake and a paleo-earthquake established for Cadarache site.

The mechanical design is a huge activity of the Cryoplant design which request close collaboration with all Parties.

2.5. Instruments and Control Design

2.5.1. Control architectures. The Cryoplant has an independent annex to the cold box building (B-52) in order to house all control systems. The Cryoplant, thanks to a mini-CODAC, is able to continue operation in case of communication loss with the ITER Main Control Room. The Instrument and Control System main design architecture has been refined with regard to [1] and confirmed during the final design. The figure 6 provides an overview of the latest architecture and technical choices.

The Plant System Host (PSH) acts as bridge which houses all interfacing software's and link with Ethernet cables, the Human Interface Machine (HMI) as well as the Programmable Logic Controller (PLC) and the Plant Interlock System (PIS).

The PLC function is supported by SIMATIC S7-400 or S7-300, whereas the PIS function is supported by SIMATIC S7-400FH in order to maintain safe and fault-tolerant controllers. Then, all PLC, PIS are connected with optical fiber to remote I/O by field bus cables leaving the annex of B-52 (a Profinet in ring network). Each Cryoplant subsystem is controlled by individual PLC.

In addition the Bently Nevada racks S3500 located in B-51 will be connected to each compressor station controllers using a Modbus TCP protocol, optical fiber cable and media converter will be used to route the signals up to the annex B-52. The aim of this link is to display on the Mini-CODAC, the values of the vibration sensors.

The Bently Nevada S3500 racks will also be linked with the "System One" server using optical fiber and media converter. The "System One" software is a powerful Bently Nevada tool dedicated to vibration analysis and monitoring at high rate.

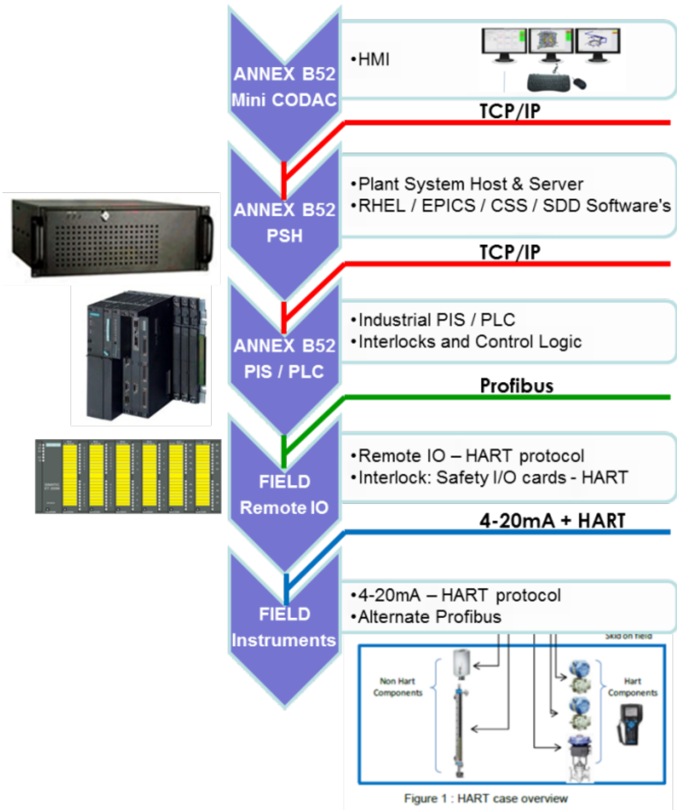

Figure 6. Instruments and Control Architecture

2.5.2. Instrument architectures. On the field, three kinds of instrument families are used:

- HART (Highway Addressable Remote Transducers) – For transmitters and proportional valves actuators on cold boxes and warm compression stations. HART is fully compatible with Siemens Profinet on specialized ET200M.
- Standard wiring 4-20 mA or 0-10 V – for non-compatible components with HART (e.g. vacuum gauges)
- Profibus DP or Profinet – for remote I/O or directly connectable components (e.g. cryogenics temperatures sensors)

ITER has chosen the HART protocol for the instruments in order to ease the configuration, the diagnostic and the maintenance done with dedicated software launched in an engineering station connected to the PLC or the Profinet I/O networks where the HART components are wired. In the field it is also possible to plug a HART pocket at several point of the architecture during maintenance.

All design choices for the control system are done, and the procurement and development is started.

3. ITER Cryoplant Construction Organization

Today, the final design of the Cryoplant is completed and the equipment manufacturing is nearing completion. The construction has been initiated. A transverse project organization is established to ensure the integrated installation of the entire Cryoplant including its buildings, infrastructures and utilities. Part of the project organization is the identification of the installation and test sequence.

3.1. Construction Organisation

In order to manage efficiently the installation, the Cryoplant is shared by zones or area (WBS) as presented in figure 7. Inside each area, a breakdown by Products and Contractor under Construction Work Package (CWP) is developed. The installation and test activities through the 18000 m^2 have requested to be split in 18 areas from 500 m^2 to 2000 m^2 each and around 500 CWP. These activities spread not only at ground level but from basement up to the roof.

The organization will enable to have a clear picture of the tasks and maintaining a safe environment for the workers due to limited co-activities. A proper installation sequence enables a high quality in right time. The schedule and the cost will be under control.

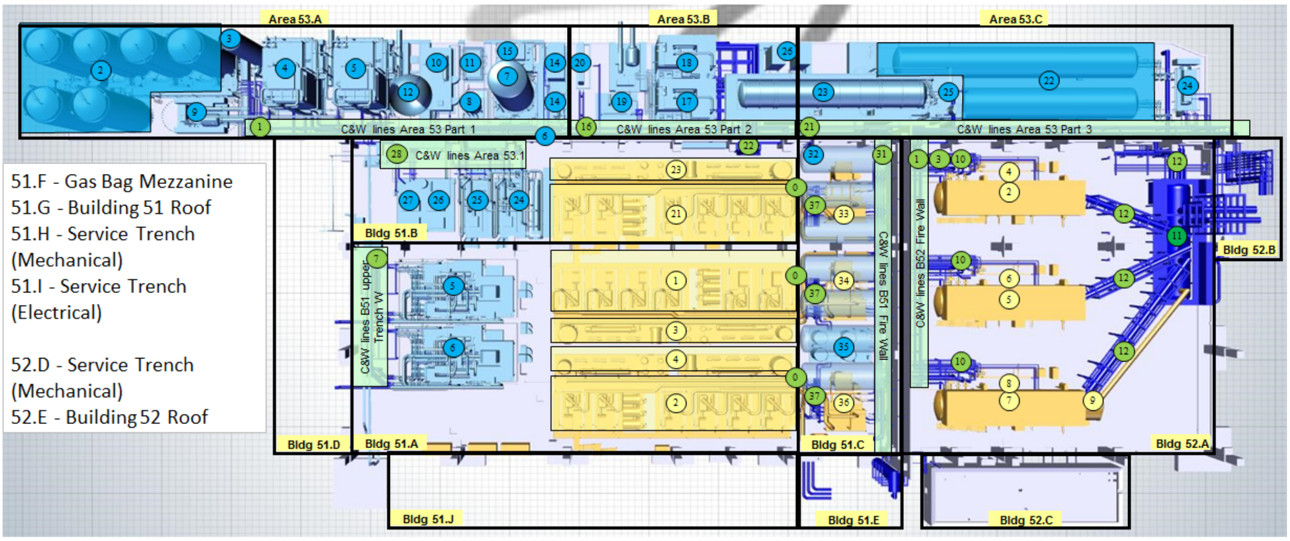

Figure 7. Cryoplant zoning (WBS).

3.2. Construction Sequence

The project manufacturing phase will end by the delivery and inspection of the equipment in a temporary storage zone on ITER site. The second phase which will last around four months will make priority for the lifting and handling of skids and large components. Construction will start during the third phase with all mechanical, piping, electrical and instruments activities. The last phase named “Mechanical Acceptance” will request to the contractor to justify that the equipment is ready to be operated.

The Figure 8 summarizes the four sequences of installation and associated constrains or expectations.

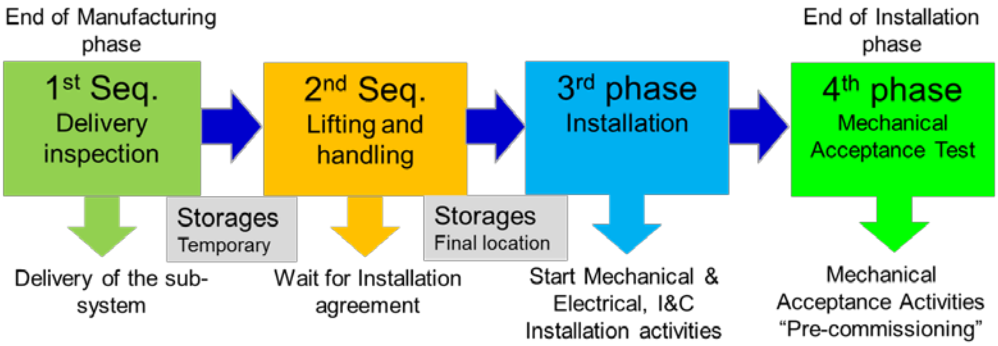

Figure 8. Cryoplant construction sequence.

This organization demands adequate storages and component management procedures. A dedicated team is working for the components logistics. Only for the Cryoplant, the team is managing 11000 tons of components which request 14000 m^2 of storage’s surface for an average storing time of 9 months.

In addition to component management another challenge consists in managing worker’s flow throughout the ITER site and buildings. We planned to provide offices for Contractor management, welfares facilities for Workers, as well as workshop and installation tools and fittings storages.

ITER is putting the final tinge on the construction organization to limit the risk and be ready to welcome all partners.

4. Project Status and Conclusion

The detail design phase of the Cryoplant is completed and all components are under manufacturing. During 2016 and the first quarter of 2017 all goods will be delivered and stored on ITER site in parallel to the civil construction of Cryoplant buildings. The installation milestone for cryogenic equipment is second quarter of 2017.

The final design of the Cryoplant is closed to the conceptual design with three LHe plants, two LN_2 plants, two 80 K Helium Loops and a recovery and purification system. Then main updated were guided by CAPEX versus OPEX studies, integration design due to surface limitation on ITER site, energy and operation loss saving and to gather function that were spread through different system on ITER site.

The ITER Cryoplant is designed to cope efficiently and reliably with unprecedented pulsed heat loads and the safety requirements of a nuclear installation.

ITER is now facing a new and exciting challenge: the integration of all components specified and designed in collaboration with Domestic Agency and industrial Partners for years.

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Disclaimer
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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Dear Reviewer,

I thank you for your valuable comments which allow me today to propose you an updated version of my Paper which should be accepted for publication.

Here below my reply to your remarks showing you how I have integrated them in my revised paper.

General remarks:
I have updated the Paper trying to justify the choice we made along the design phase. I tried in this paper to present the evolution aspect in many differents areas such like the layout and integration, the mecanical, the process, the process control and the Instrument and Control System. The updated choice are presented or compared.
In a Paper limited in page numbers, it is a difficult exercice to go in deep on all matter.
My goal, for the Reader and the Community, was by presenting many aspects to rise questions that I will be please to reply. As well this paper will be a support to future papers presenting in detail the final design.

As you well notice, such reporting paper is to propose to the reader a large overview of the ITER project and the reader is able to contact the ITER Team to have reply and exchange on all aspects relating to a design of a cryogenic system.

Language:
Your comments were fully justified and I made a deep review with the co-authors.

Disclaimer:
This sentence is imposed by ITER Organization legal and publication department even if the paper pass through a review process including hierarchy/management. We are not allow to publish a Paper without this sentence.

References:
You are right and it is one of my mistake which will now allow the reader to see where the reference are used and helpful for the reader to have a clearer view of the evolution of the ITER design.
The Reader is now able to link the previous publication with this one in order to understand better the design evolution of the ITER Cryogenic System.
It is always difficult when we are fully involved and dedictated in a project to transmit precise and specific information to a Reader not knowing all ins and outs.

I hope that my paper will know retain all you attention and will be published. I have put in this paper a lot of my experience and time to transmit and share part of the ITER adventure.

Best Regards,

Emmanuel Monneret.